T2K-LAr: A proposed Liquid Argon TPC detector for T2K

http://neutrino.ethz.ch/

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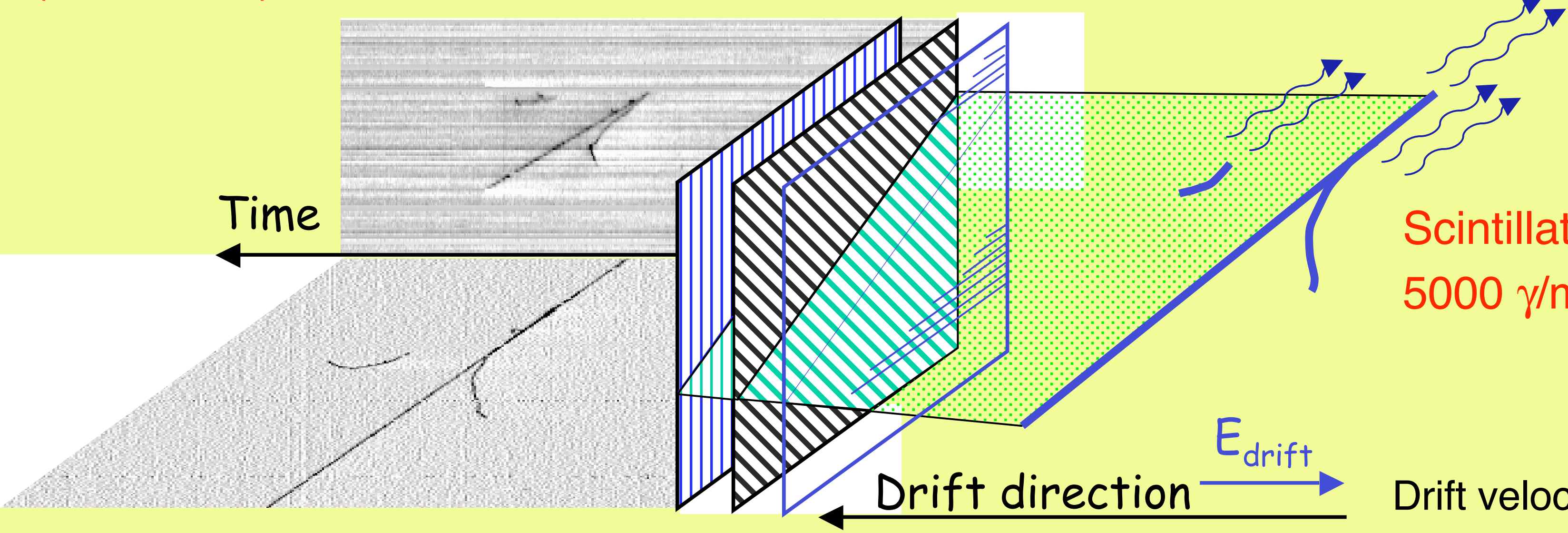
CHIPP Meeting, 28-29th September 2005
PSI Villigen

The Liquid Argon TPC principle

Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L



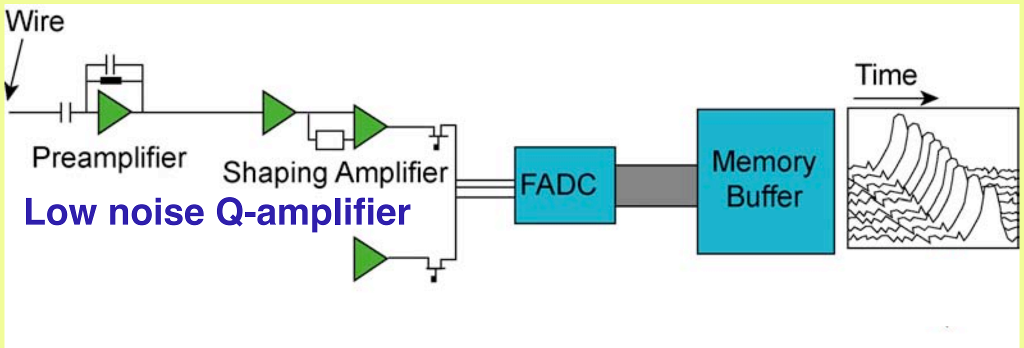
Scintillation light yield ~ 5000 γ/mm @ 128 nm

Drift velocity ≈ 2 mm/μs @ 1 kV/cm

Drift electron lifetime:

$$\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}$$

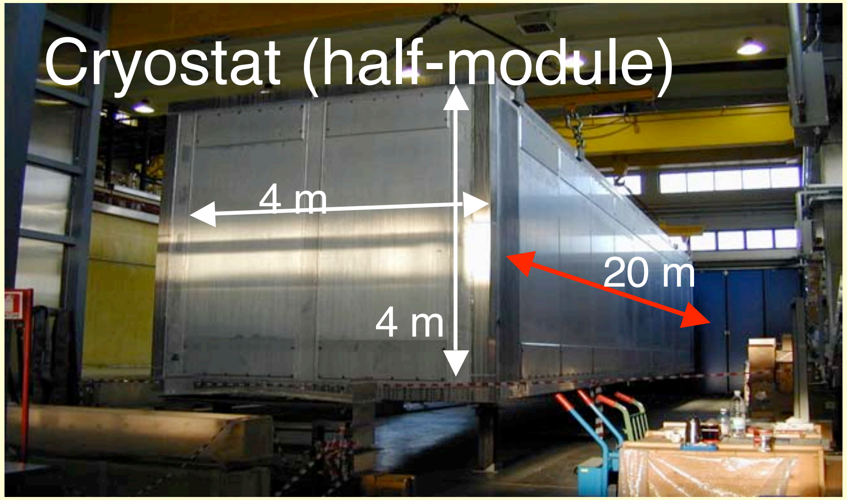
Purity < 0.1ppb O_2-equiv.

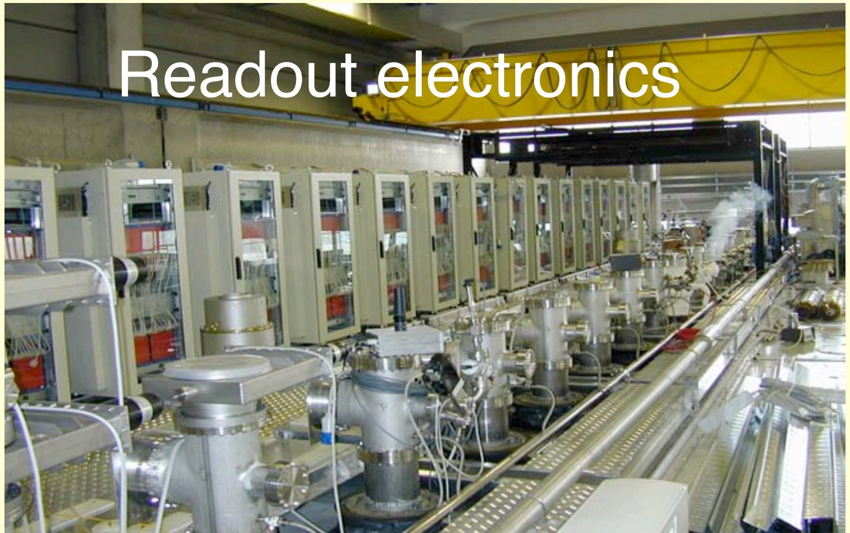


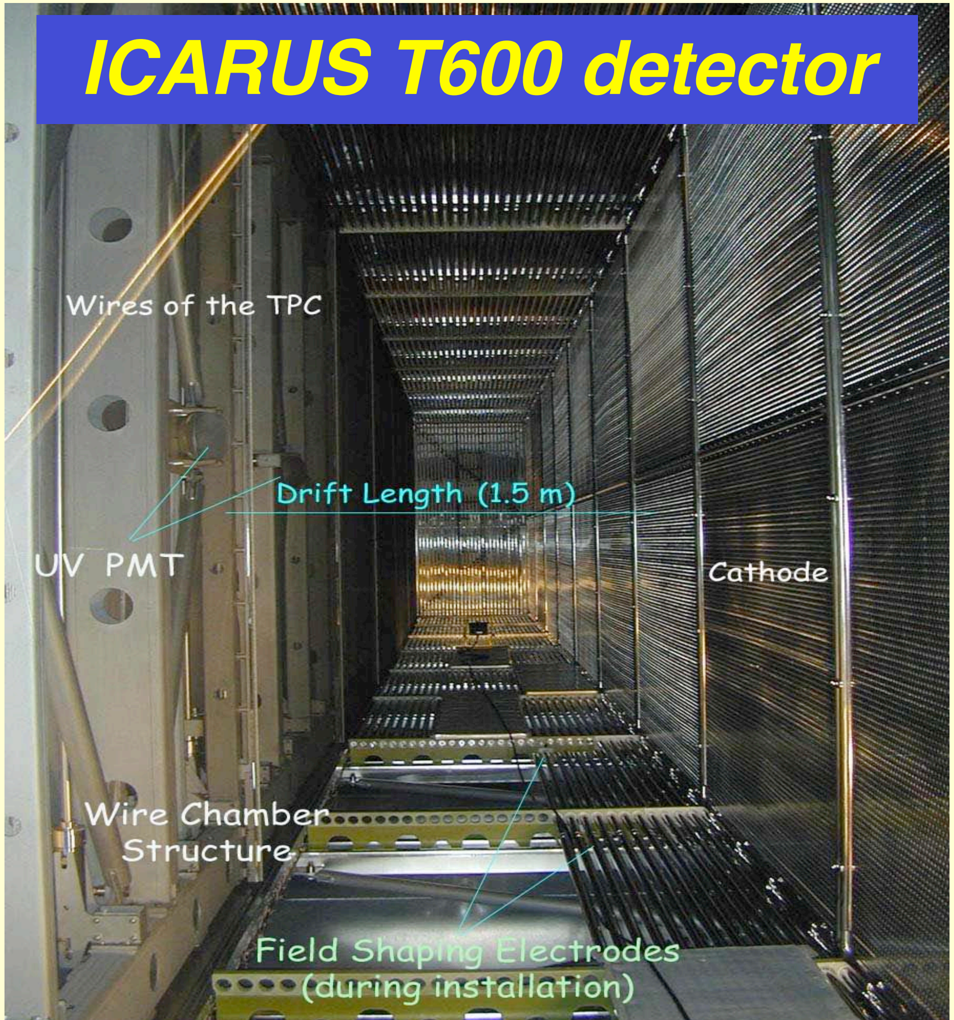
Low noise Q-amplifier

Continuous waveform recording → image

- The Liquid Argon Time Projection Chamber: a new concept for Neutrino Detector, C. Rubbia, CERN-EP/77-08 (1977).
- A study of ionization electrons drifting large distances in liquid and solid Argon, E. Aprile, K.L. Giboni and C. Rubbia, NIM A251 (1985) 62.
- A 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A332 (1993) 395.
- Performance of a 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A345 (1994) 230.
- The ICARUS 50 l LAr TPC in the CERN neutrino beam, ICARUS Collab, hep-ex/9812006 (1998).



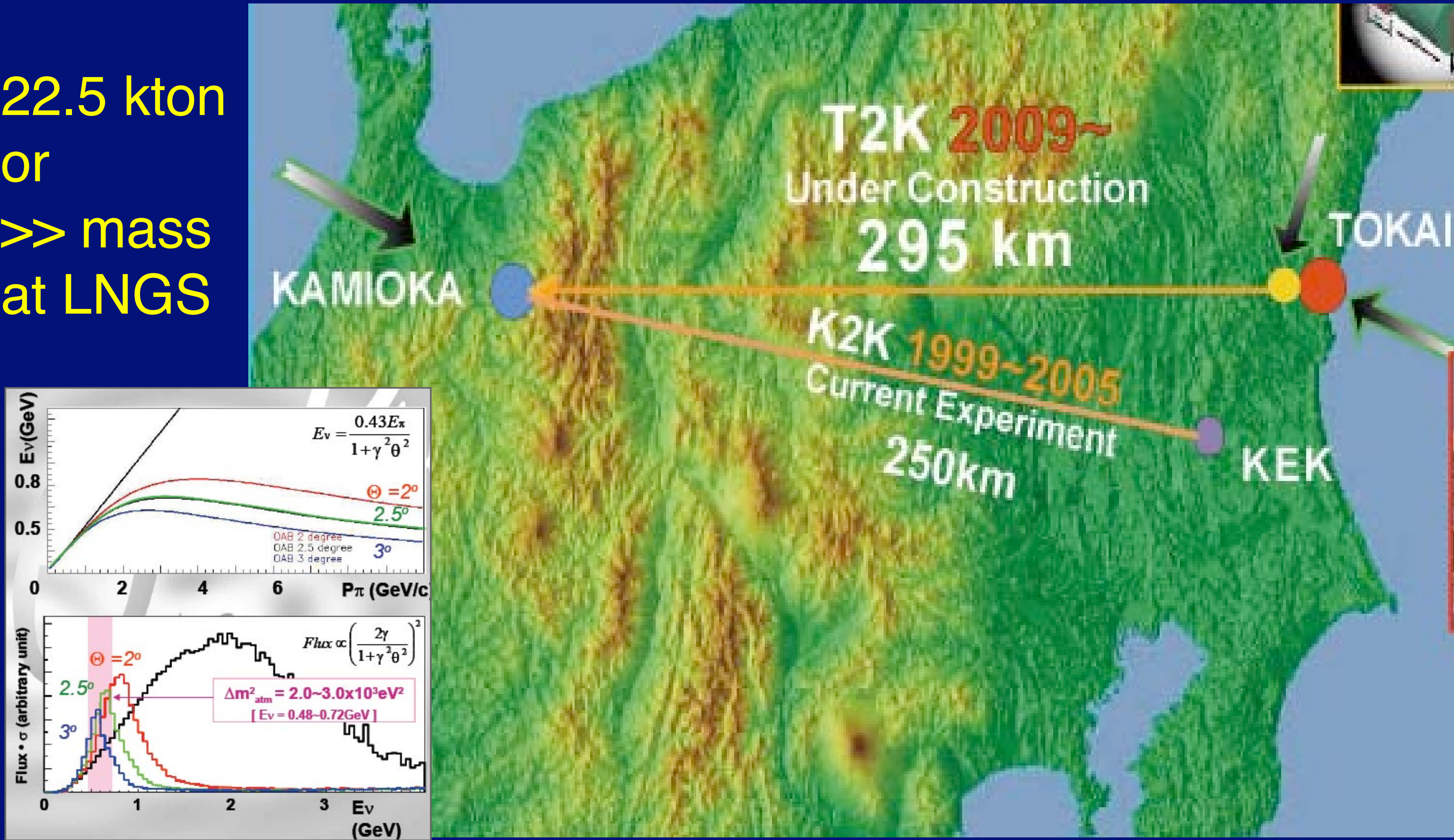




- Design, construction and tests of the ICARUS T600 detector, ICARUS Collab, NIM A527 329 (2004).
- Study of electron recombination in liquid Argon with the ICARUS TPC, ICARUS Collab, NIMA523 275-286 (2004).
- Detection of Cerenkov light emission in liquid Argon, ICARUS Collab, NIM A516 348-363 (2004).
- Analysis of the liquid Argon purity in the ICARUS T600 TPC, ICARUS Collab, NIM A516 68-79 (2004).
- Observation of long ionizing tracks with the ICARUS T600 first half module, ICARUS Collab, NIM A508 287 (2003).
- Measurement of the muon decay spectrum with the ICARUS liquid Argon TPC, ICARUS Collab, EPJ C33 233-241 (2004).

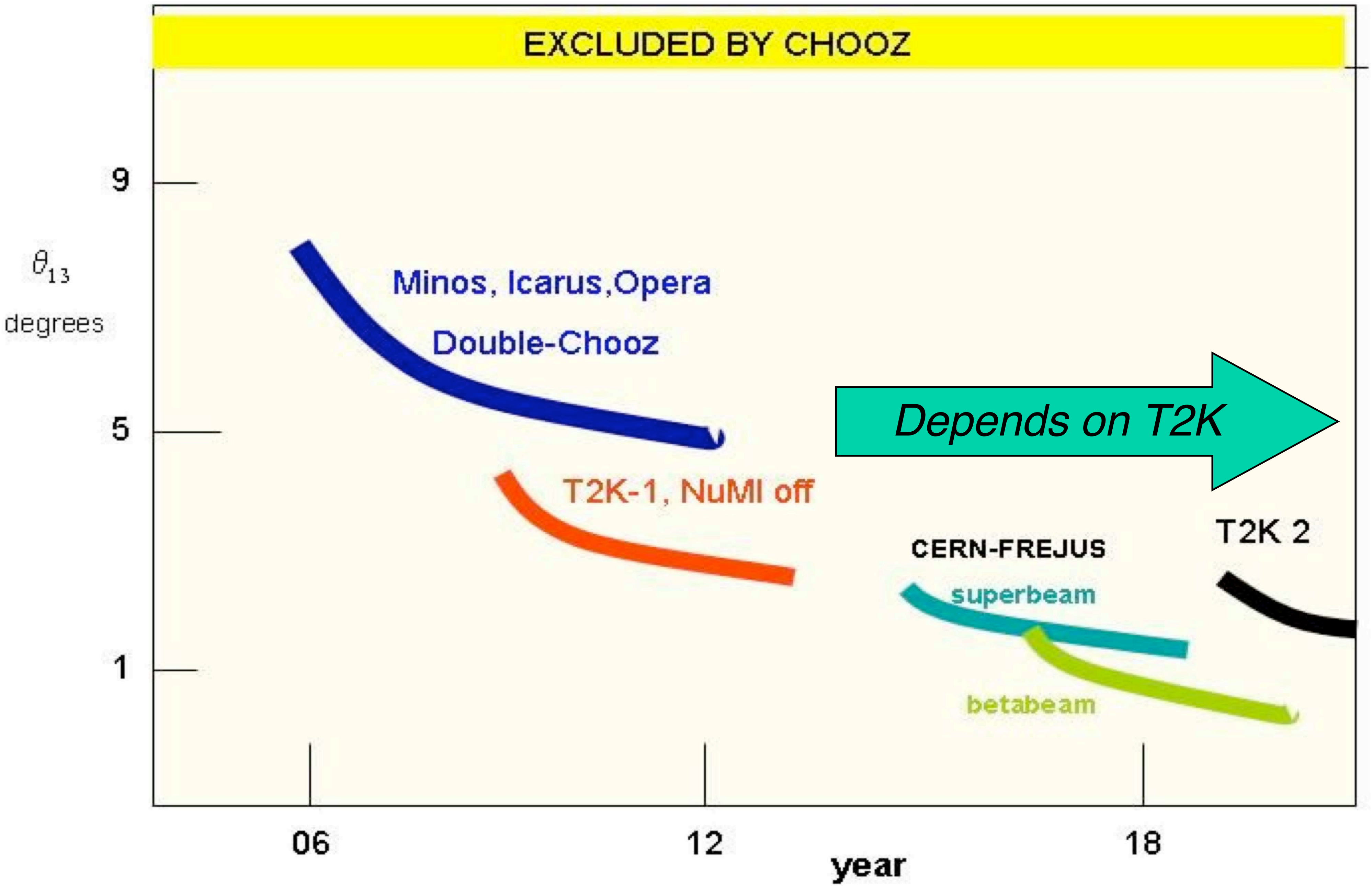
The first Super-Beam: T2K from Tokai to SK

22.5 kton
or
>> mass
at LNGS



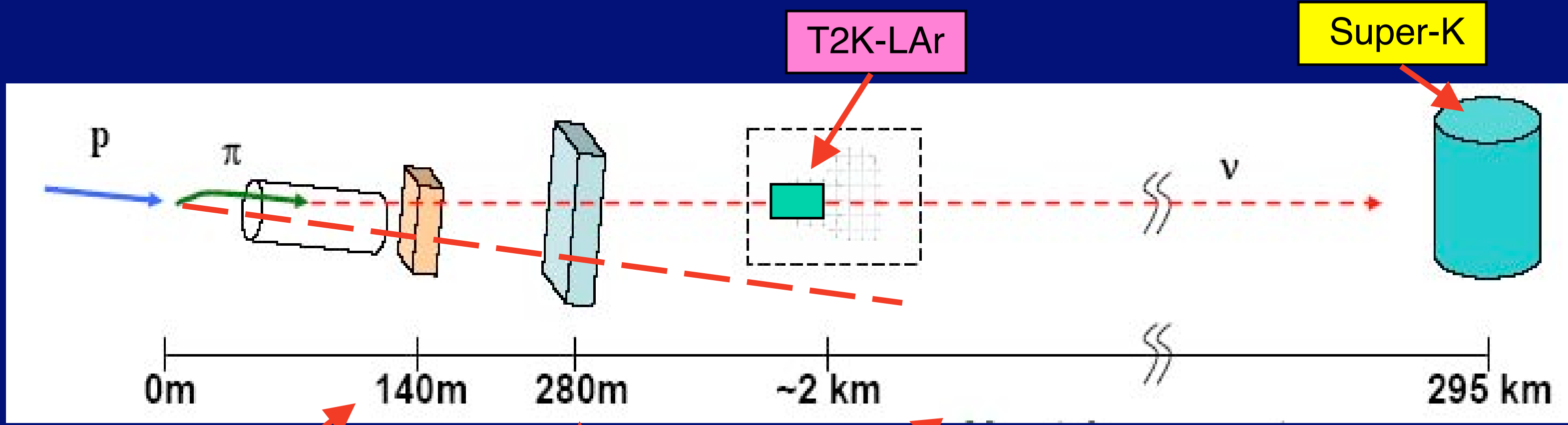
0.75
MW or
>2x
CERN
SPS
power

- Low energy neutrino superbeam (less than 1 GeV) from Tokai to Super-Kamiokande starting in 2009 and reaching power of 1.35 MW by 2012 from 40 GeV proton synchrotron (>10^{21} p.o.t./year). Off-axis by 2.5°.
- Foreseen upgrades: 4 MW power and (eventually) 1000 kton Hyper-K
- Very interesting ideas: LBL detector in Korea / China ?



EXCLUDED BY CHOOZ
9
θ_{13}
degrees
5
1
Minos, Icarus,Opera
Double-Chooz
Depends on T2K
T2K-1, NuMI off
CERN-FREJUS
superbeam
betabeam
T2K 2
06
12
18
year

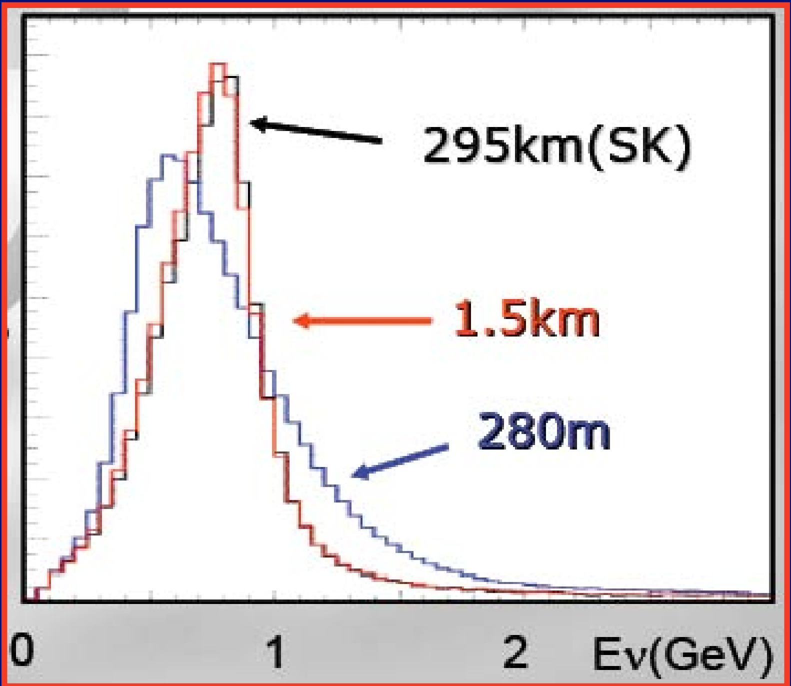
Off-axis beam and the various T2K detectors



μ monitor (beam direction and intensity)

ν energy spectrum and intensity

Same spectrum as SK, BG measurement

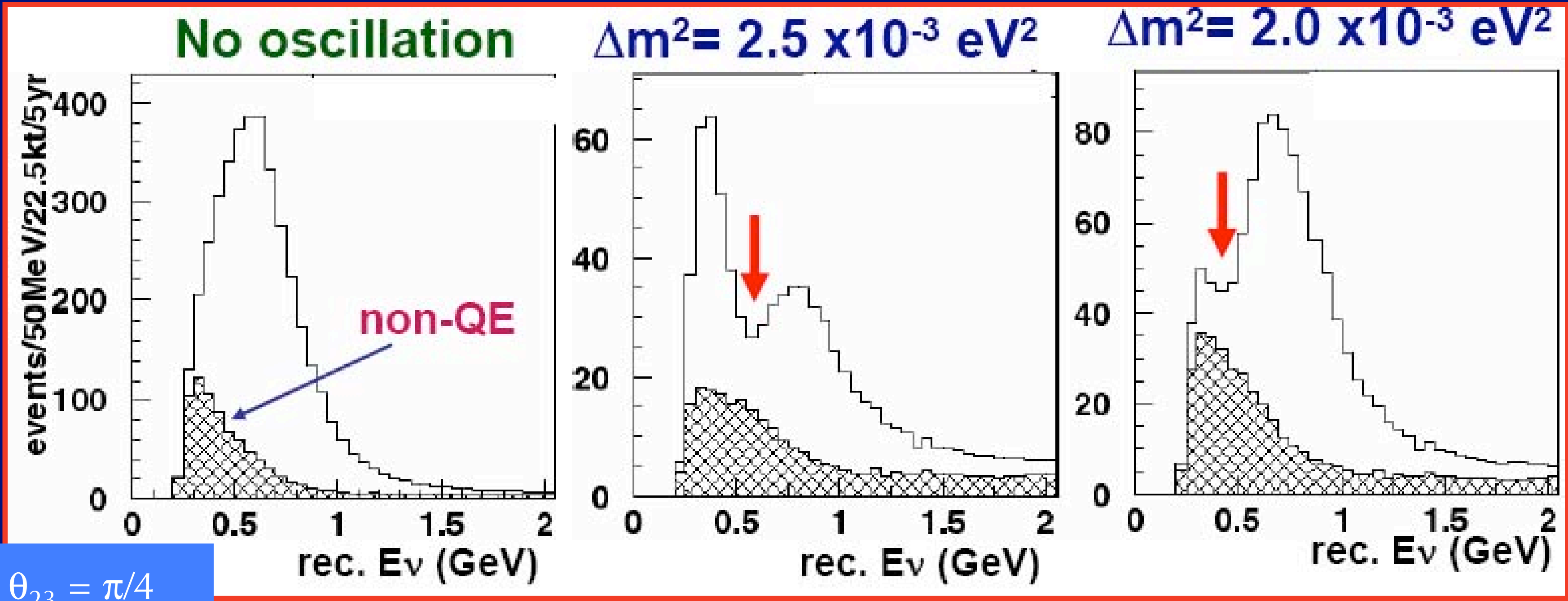


- low E_ν (<1 GeV) Super-Beam: $>10^{21}$ pot/year @ 40 GeV (≈1.35 MW by 2012)
- SK detector: 22.5 kton x year
- @ 2° → 3000 ν_μ CC/year (x10 w.r.t. K2K)
- 0.2% ν_e contamination and $\pi°$ BG

Importance of near detectors: **main systematic error in K2K** comes from difference in near/far spectra

T2K ν_μ disappearance

$P(\nu_\mu \rightarrow \nu_x) \sim \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2 (\Delta m^2_{23} L/ 4E_\nu)$

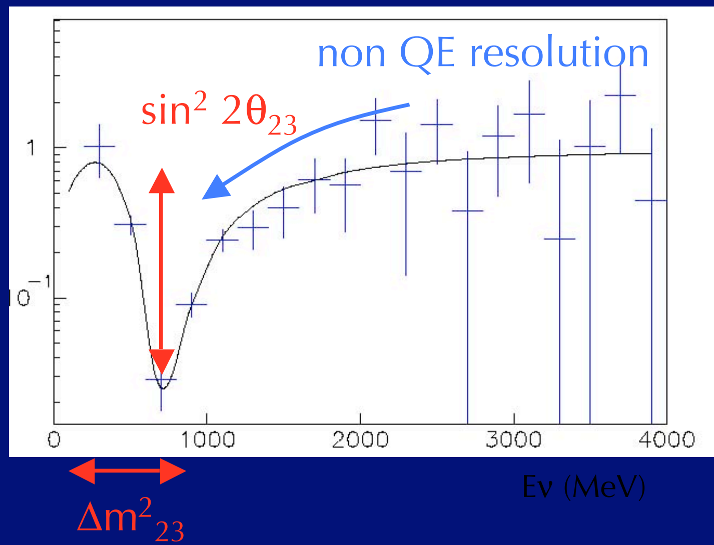


assume $\theta_{23} = \pi/4$

5 years of running

Sensitivity: $\delta(\Delta m^2) < 10^{-4}\, eV^2$

$\delta(\sin^2 2\theta_{23}) \sim 0.01$



A good QE/nQE measurement is fundamental to reduce systematic errors: in K2K its contribution to the systematics was 10%.

$\Delta m^2 = 3 \times 10^{-3}\ \mathrm{eV}^2$ and $\sin^2 2\theta_{\mu e} = 0.05$

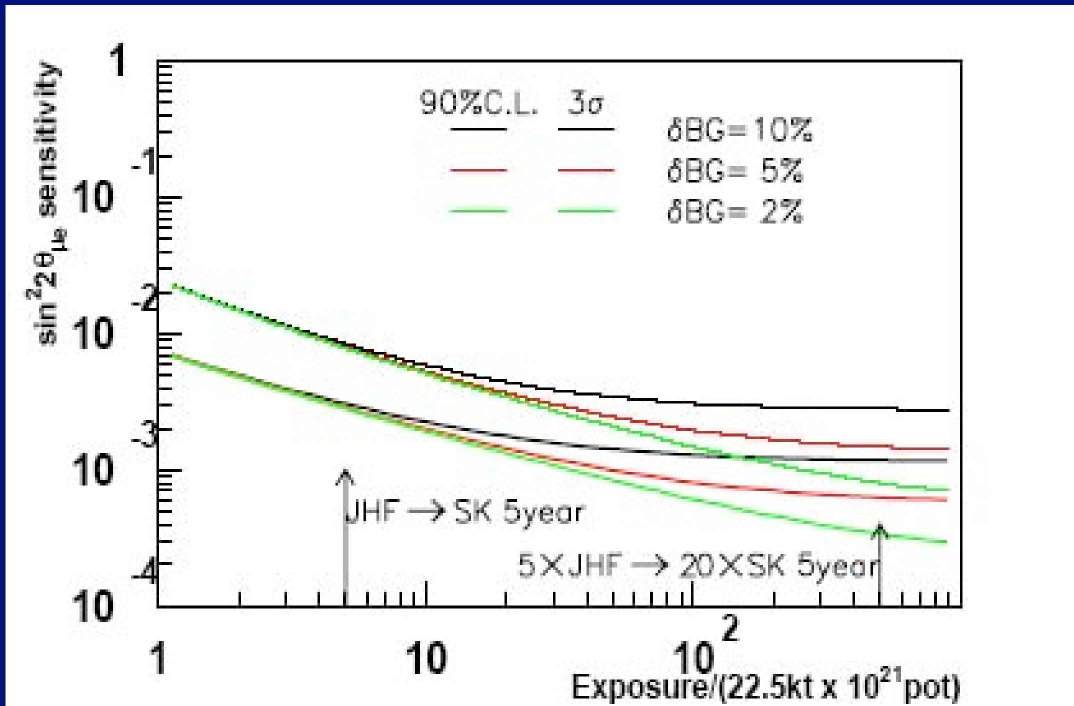
T2K ν_e appearance: measurement of θ_{13}

	$\nu\mu$C.C.		$\nu\mu$N.C.		Beam νe		Osc'd νe	
Generated	10713.6	%	4080.3	%	292.1	%	301.6	%
1R e-like	1[illegible]	0.1	24[illegible]1	6.1	68.4	23.4	203.7	67.5
e/π^0 sep.	3.5	0.03	23.0	0.6	21.9	7.5	152.2	50.4
.4 <Eν<1.2	1.8	0.02	9.3	0.2	11.1	3.8	123.2	40.8

$5\mathrm{x}10^{21}$ pots

Sensitivity: $\sin^2(2\theta_{13}) > .01$

Beyond $5\mathrm{x}10^{21}$ pots



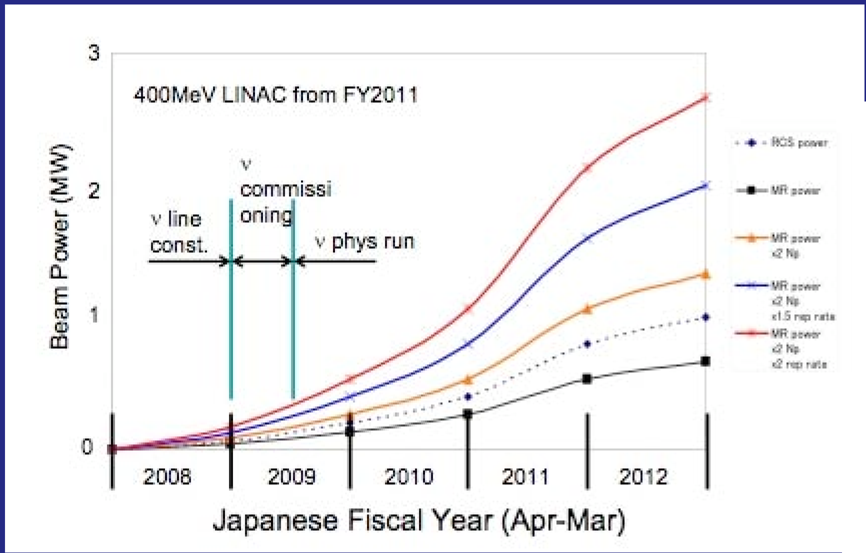
Background:

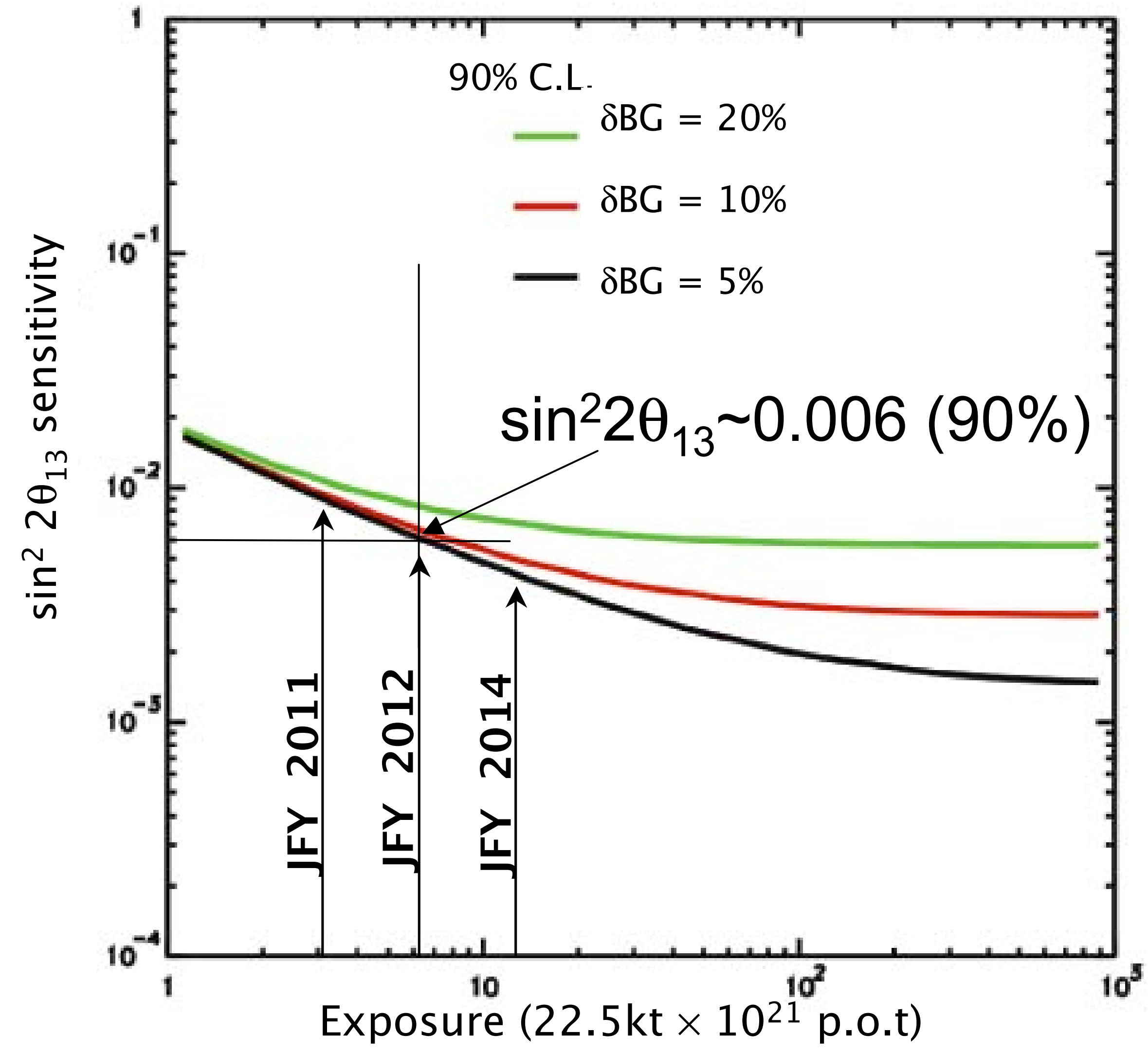
Beam ν_e : ν_e/ν_μ flux ~ 0.4% at peak.

NC π^0 production : 2 rings merged to 1 ring.

Very different systematics: measure them separately.

T2K ν_e appearance: expected timescale





<u>Upgraded intensity</u>:

With doubling of protons in bunches a power of 1.35 MW should be reachable by 2012 yielding ≈3x10^{21} p.o.t./year

Beyond 2011, systematic error must be below 10% to be negligible !

T2K-2km working group (27 institutes, 93 members)

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Wroclaw University (Poland):	J. Sobczyk
Yale University (USA):	A. Curioni, B.T. Fleming

Motivation for a 2km complex

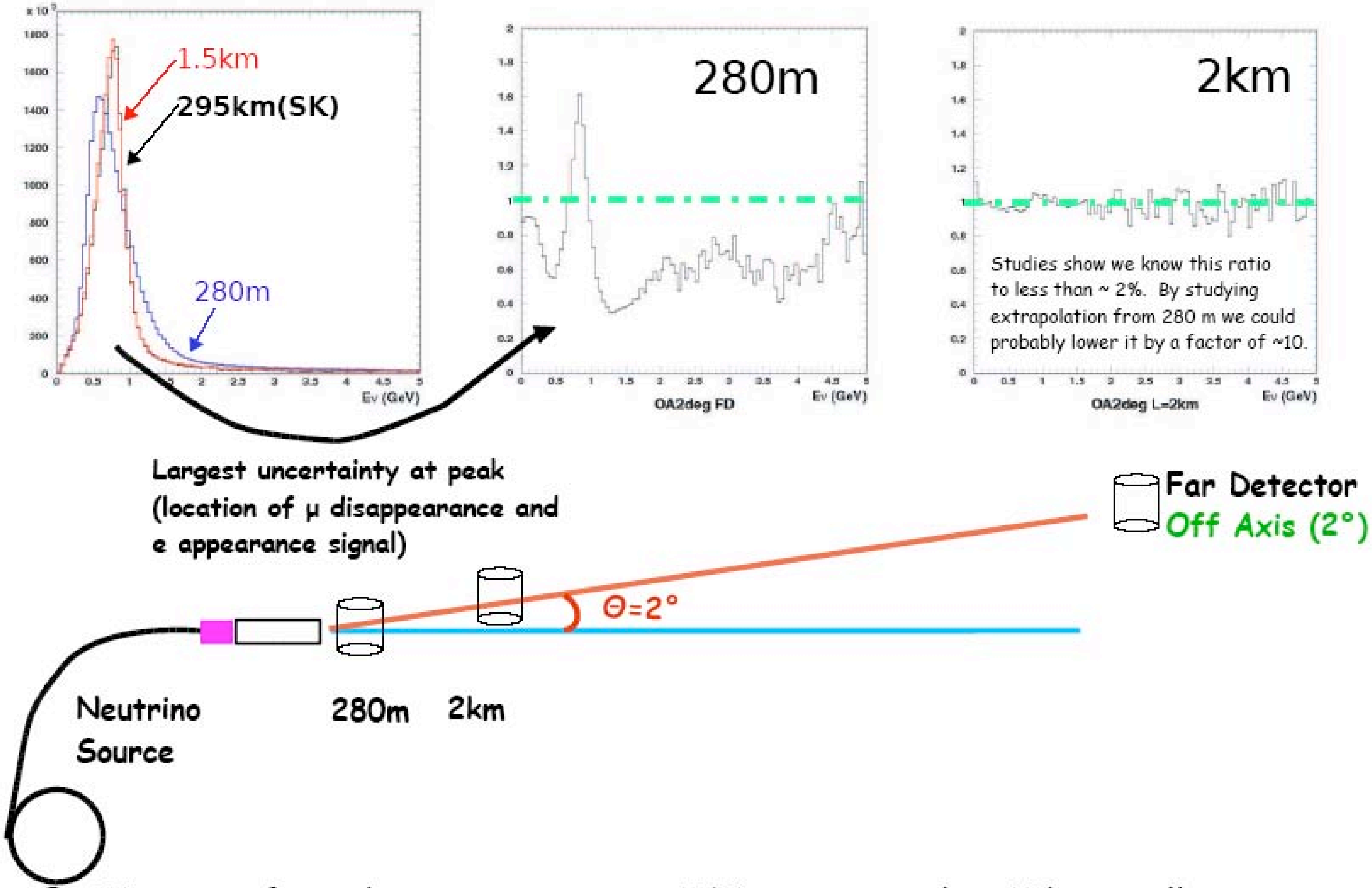
- The high statistics disappearance measurement will require a precise control of all sources of systematic errors (e.g.N(Eν)=flux(Eν)*cross-section(Eν), reconstruction in SK, ...)
- The high-sensitivity exploratory appearance search requires a control of all sources of background in SuperK at a level $<<10^{-2}$.
- A signal excess would require a cross-check with a WC detector at 2 km and the ultimate θ_{13} sensitivity will improve with a 2 km WC detector.

$\Rightarrow$ 1 kton near Water Cerenkov detector is an an important asset for T2K.

- 1 kton WC detector profits if operated in conjunction with a muon ranger for escaping muons, and a 100 ton fine grained detector, able to reconstruct recoiling protons, low momentum hadrons, asymmetric decays of π0, etc., in an unbiased way

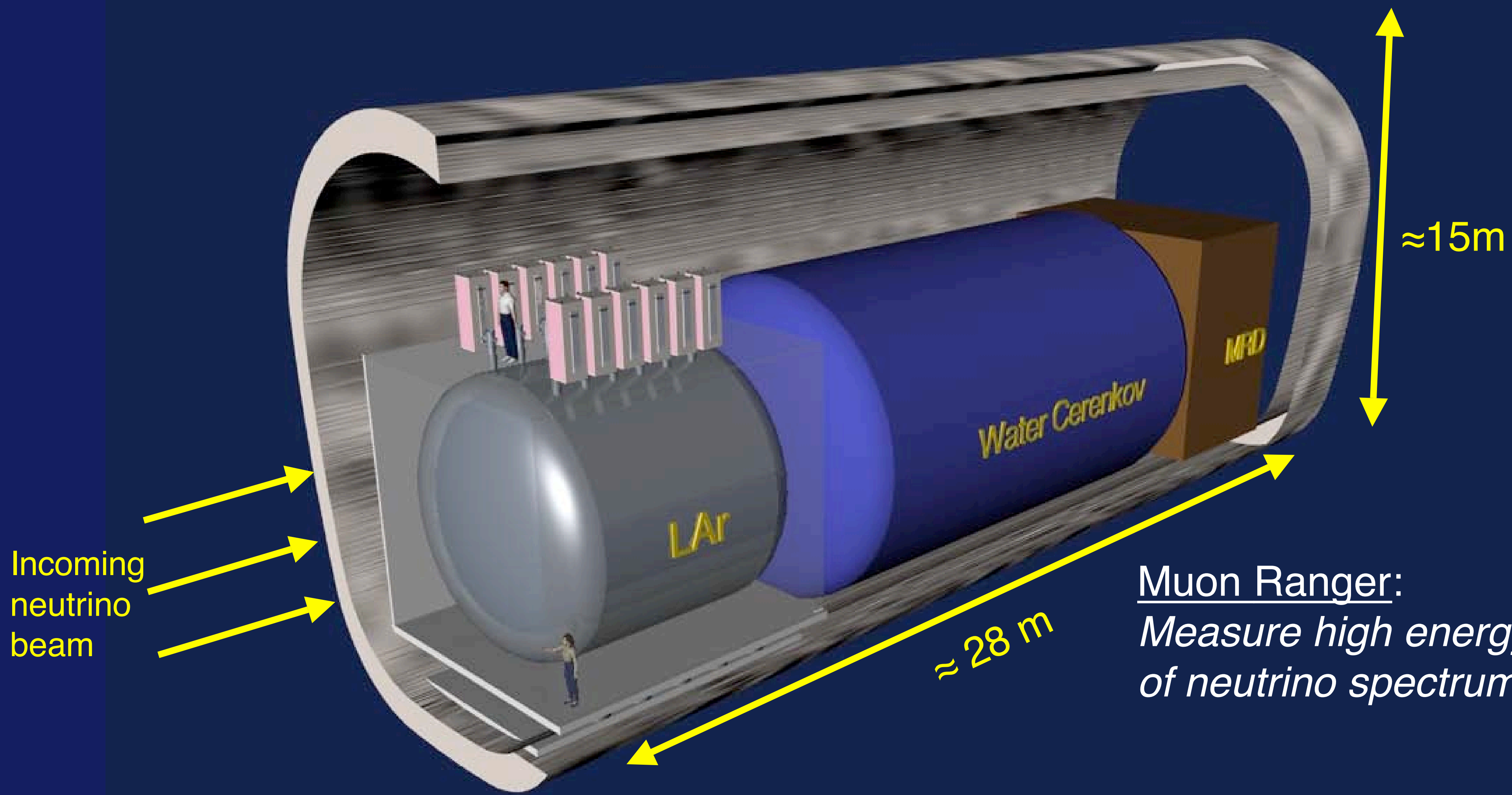
$\Rightarrow$ Complement Water Cerenkov with LAr TPC + muon ranger.

Far/Near ν Flux Ratio vs. Detector Distance



@ ~2km away from the neutrino source F/N ratio spread < ± 5% over all energies.

Artistic view of 2km underground facility with three subsystems

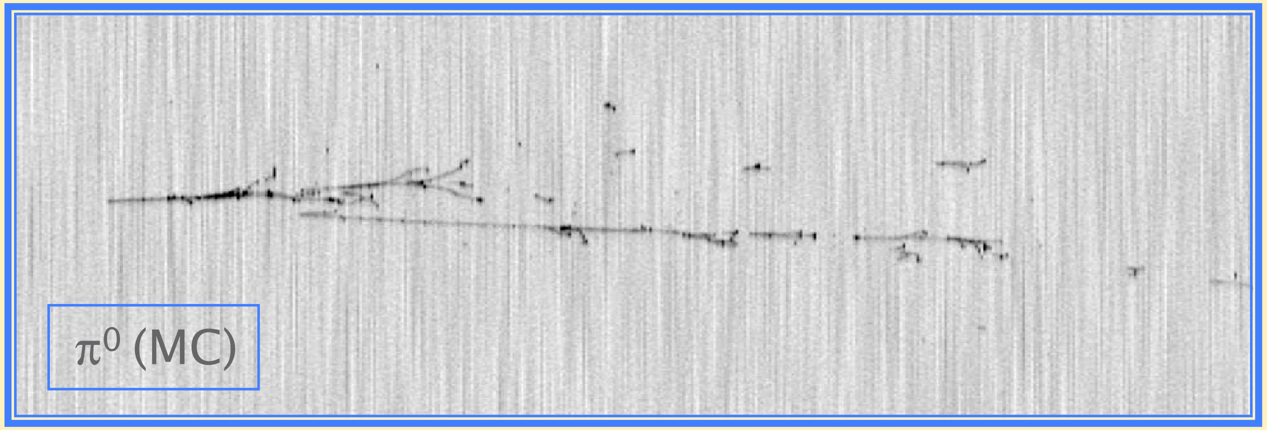


Muon Ranger:
Measure high energy tail of neutrino spectrum

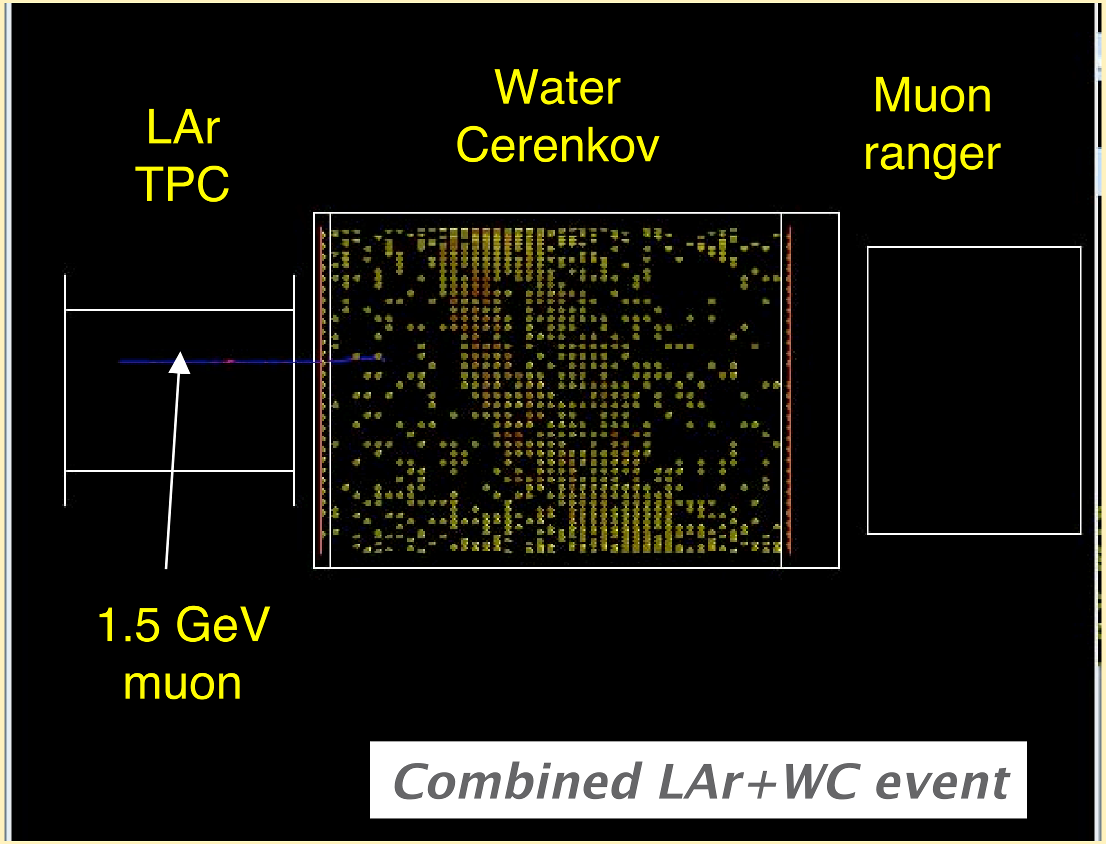
Liquid Argon detector:
Exclusive final states
Frozen water target

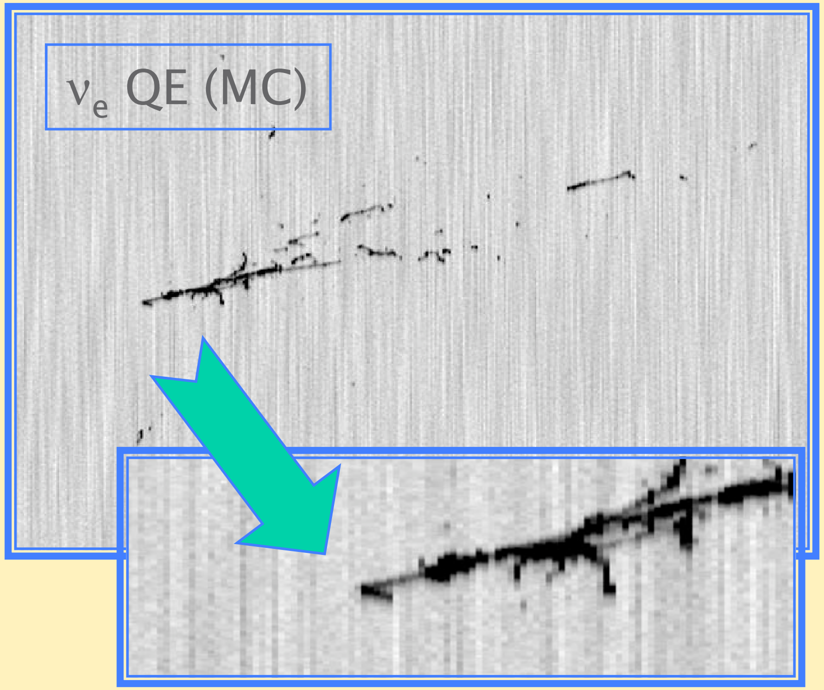
Water Cerenkov detector:
Same detector technology as SK
≈1 interaction/spill/kton

Examples of combined WC+LAr events at 2 km

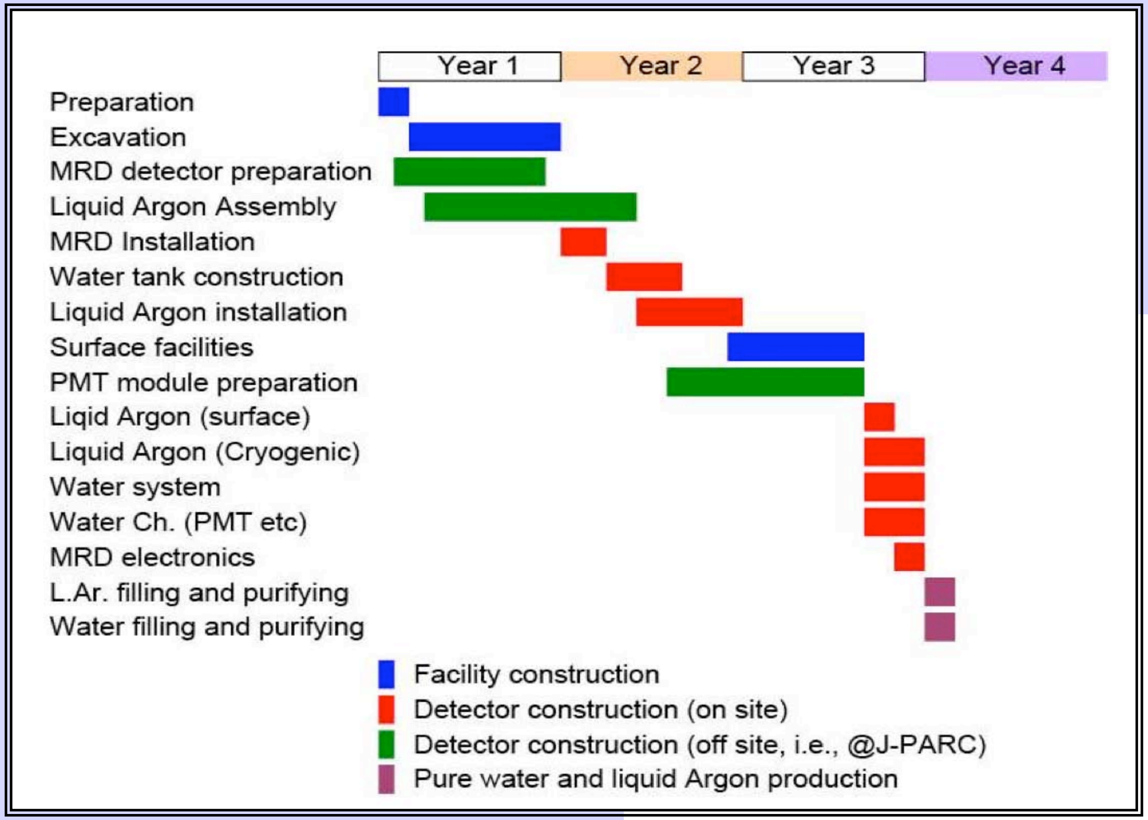


High granularity: Sampling = 0.02 X_0



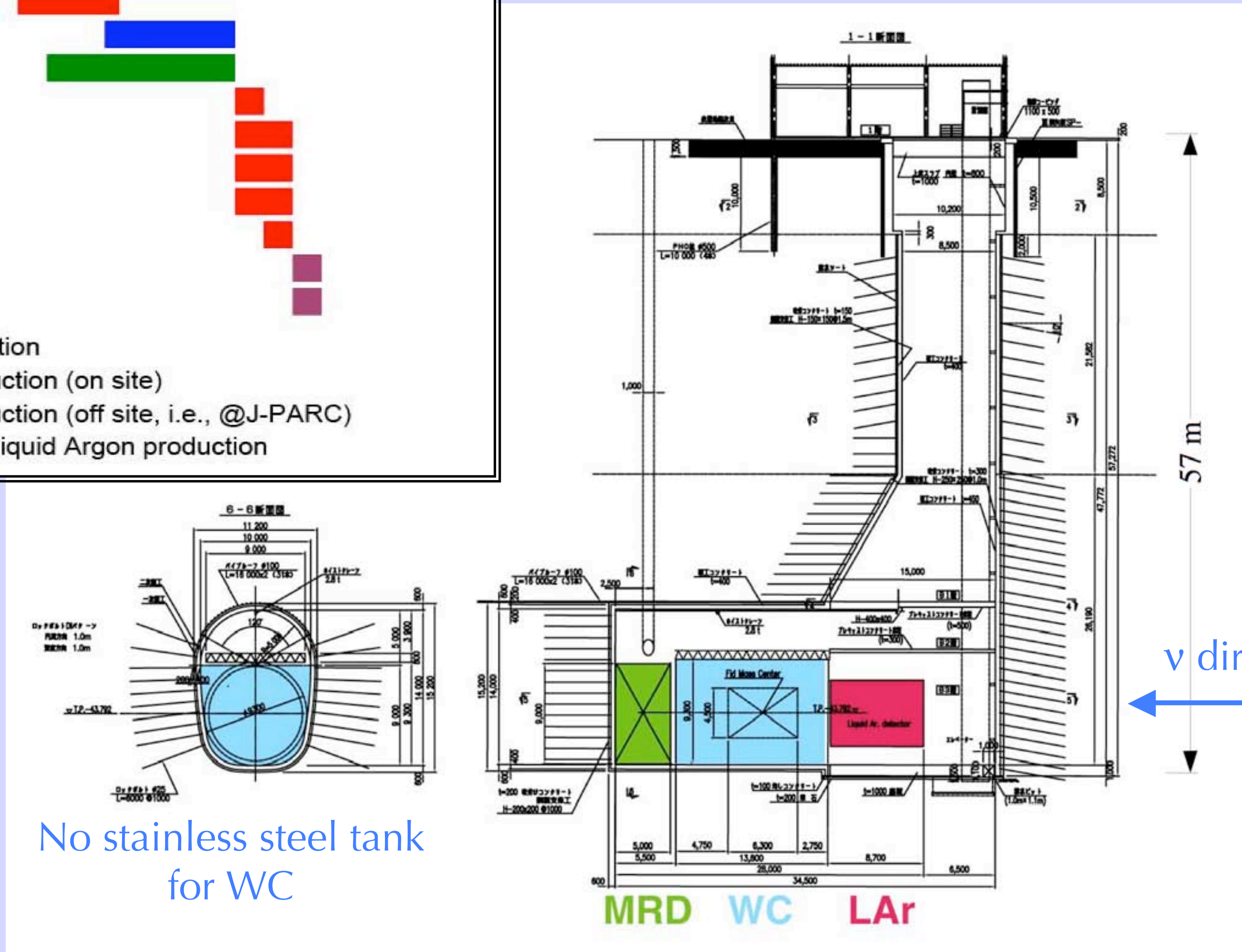


2km detector hall and construction schedule



3 years construction schedule

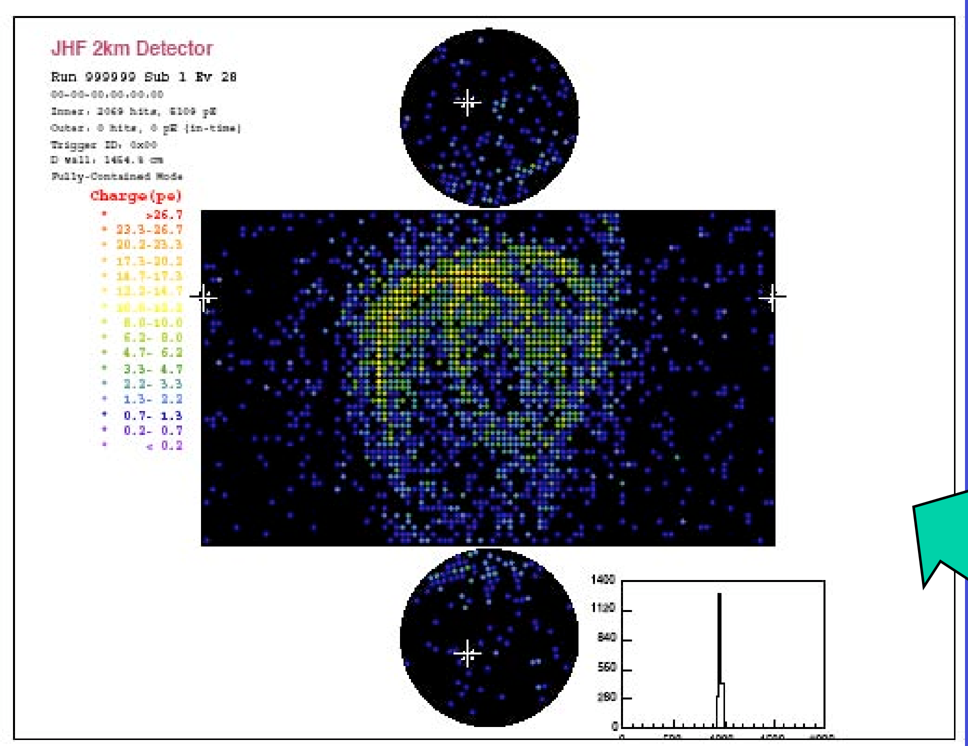
Arranged for LAr to be installed last



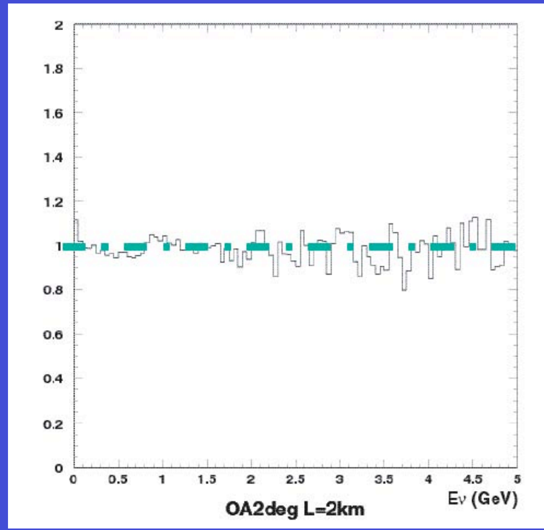
No stainless steel tank for WC

ν direction

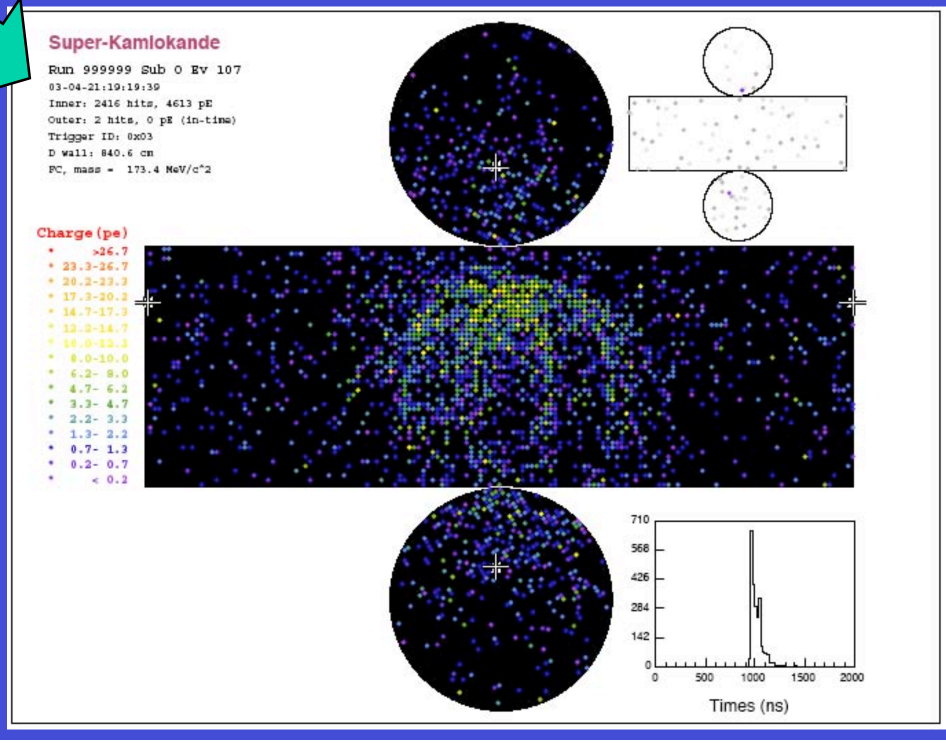
Why 2km WC?



Near/far ratio=1



SuperK @ 295 km



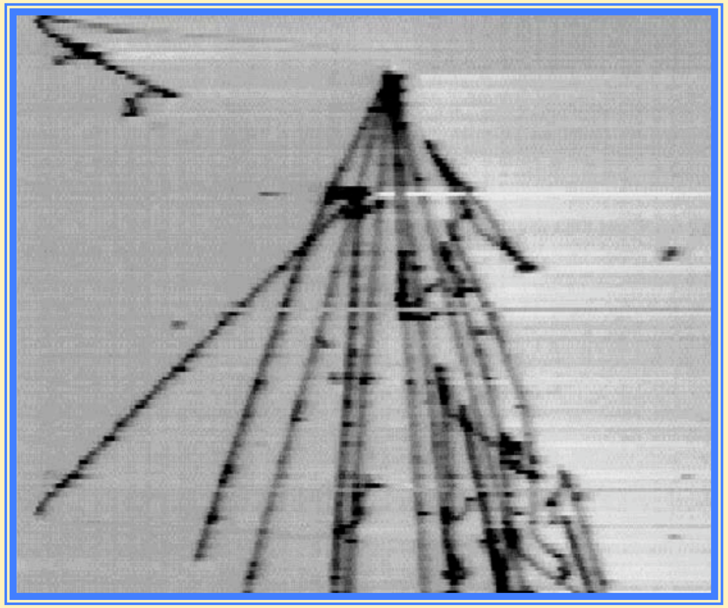
WC @ 2 km

- Same target as far detector.
- Same flux as far detector.
- Same event reconstruction as far detector ⇒ minimize systematics in prediction at far detector.
- High statistics: ~ 1 interaction per spill per kton.
- Low cost/ton, well known technology.

Why 2km LAr TPC? (1)

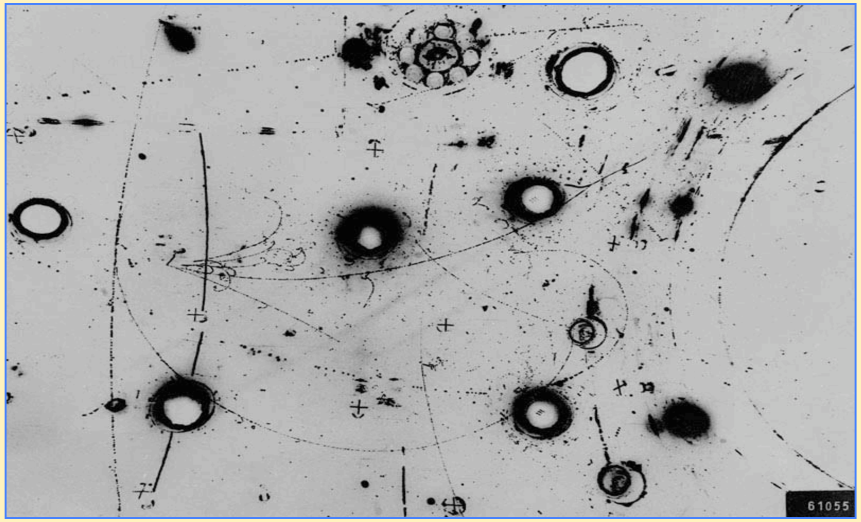
- **Fully active, homogeneous, high-resolution device** ⇒ high statistics neutrino interaction studies with bubble chamber accuracy .

Real event in ICARUS



High granularity: Sampling = 0.02 X_0
"bubble" size ≈3×3×0.4 mm^3

Gargamelle bubble chamber

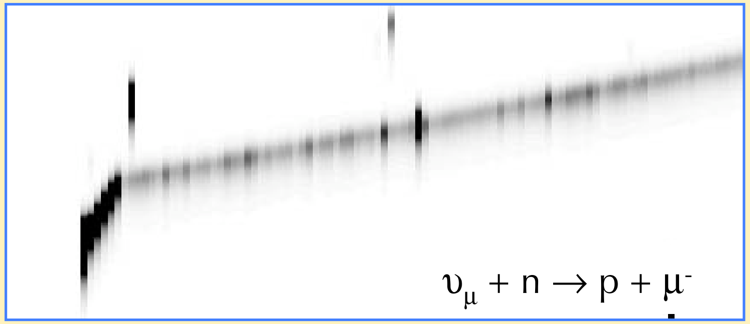


bubble diameter ≈3mm

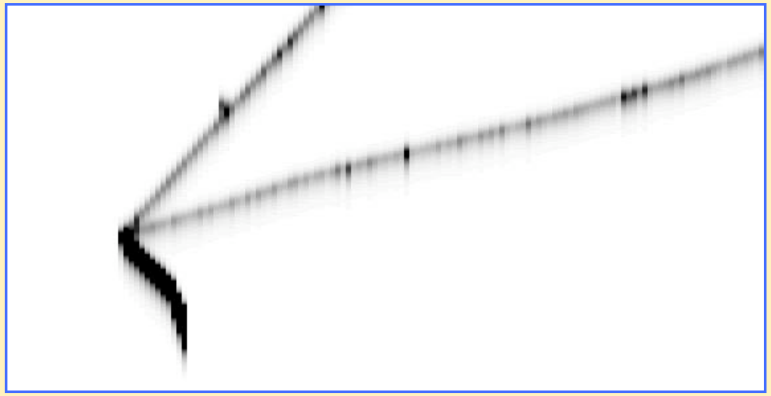
Capable of 1-event discovery…

Why 2km LAr TPC? (2)

- Reconstruction of low momentum hadrons (below Cherenkov threshold), especially recoiling protons.
- Independent measurement of off-axis flux and QE/nonQE event ratio.



MC QE event.
Proton momentum = 490 MeV/c



MC nQE event.
Pion+ momentum = 377 MeV/c, Proton momentum = 480 MeV/c

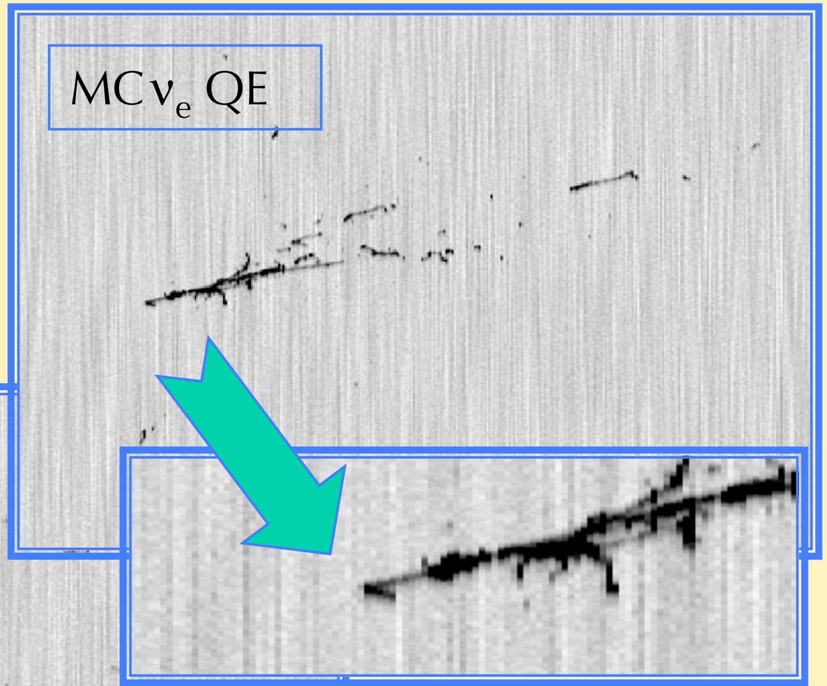
Protons

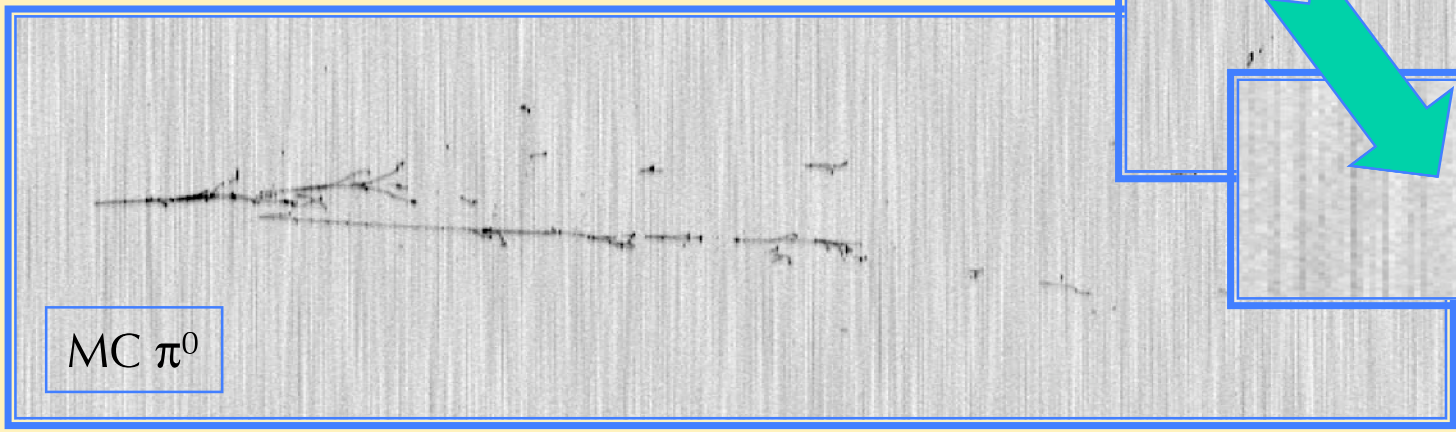
Kinetic energy T (MeV)	Momentum p (MeV/c)	Range in LAr (cm)
10	43	0.14
40	280	0.93
70	370	4.19
100	446	7.87
300	813	51.9
500	1094	116

Cherenkov threshold in Water p = 1070 MeV/c

Why 2km LAr TPC? (3)

- Exclusive measurement of νNC events with clean π^0 identification for an independent determination of systematic errors on the NC/CC ratio.
- Measurement of the intrinsic ν_eCC background.



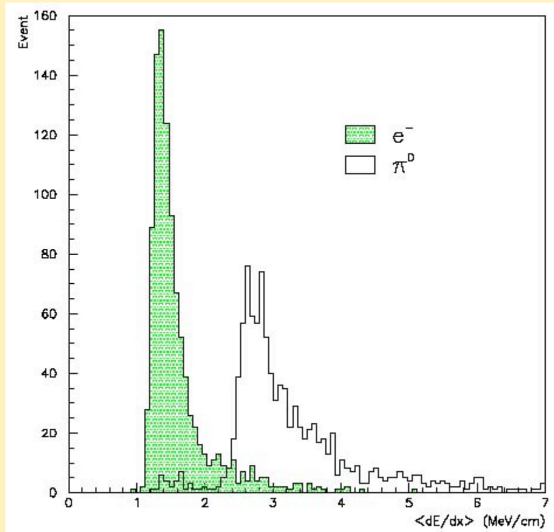


When vertex known, combine with probability to convert within 1 cm:
$\Rightarrow$ 5.4%

Combined, aim at:
$\Rightarrow$ **0.2% π^0 efficiency by imaging for 90% electron efficiency**

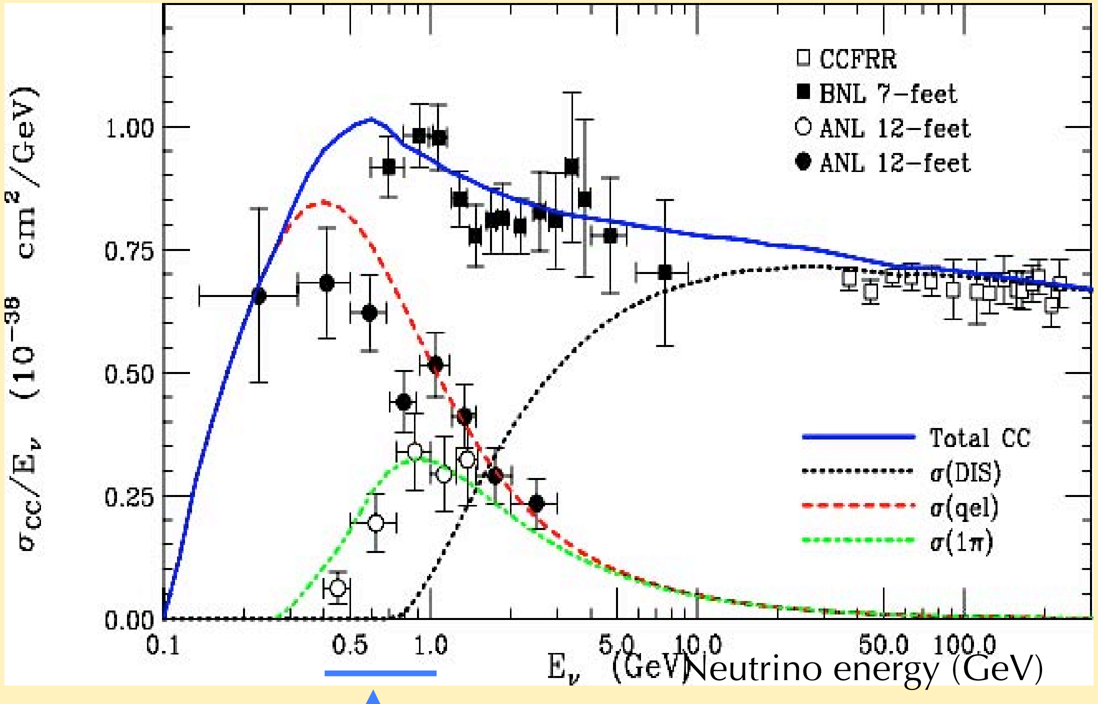
dE/dx cut efficiency:

Energy (GeV)	π^0 efficiency (%)	$< dE/dx >_{cut}$ (MeV/cm)
0.25	6.5	2.13
0.5	5.5	2.19
1	3.7	2.21
2	2.7	2.10



Why 2km LAr TPC? (4)

- Collection of a large statistical sample of neutrino interactions in the GeV region for the study of the quasi-elastic, deep-inelastic and resonance modelling and of nuclear effects.



Maximum oscillation effect

≈120'000 QE events/yr/100 ton
≈70'000 non-QE events/yr/100 ton

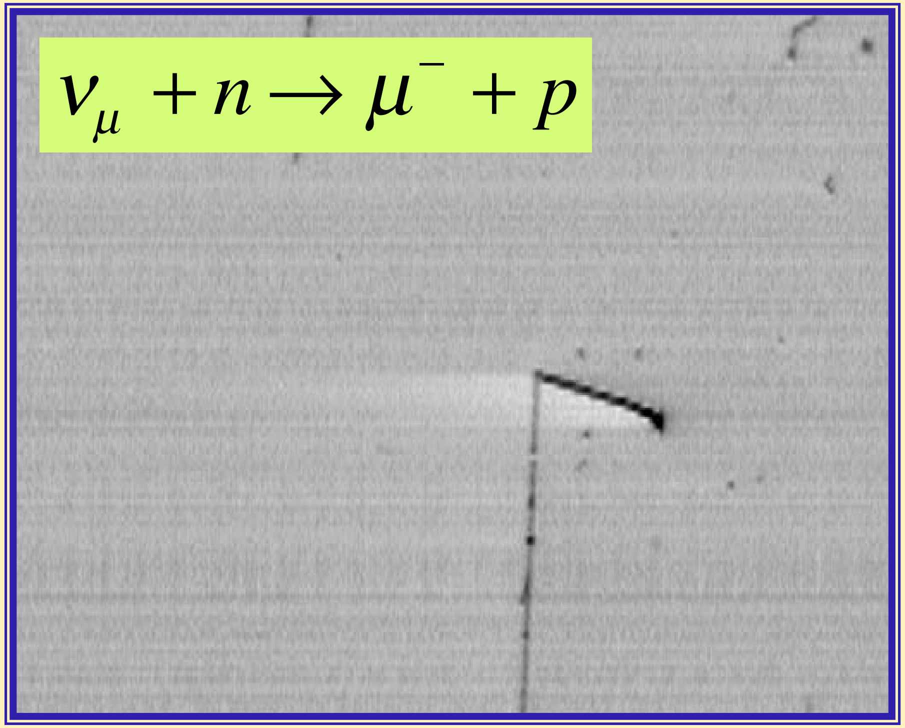
A fundamental milestone for the LAr TPC technique ! Extremely valuable experience for future large LAr detectors (in-situ R&D!)

Neutrino interactions in 50 liter exposed to CERN WANF

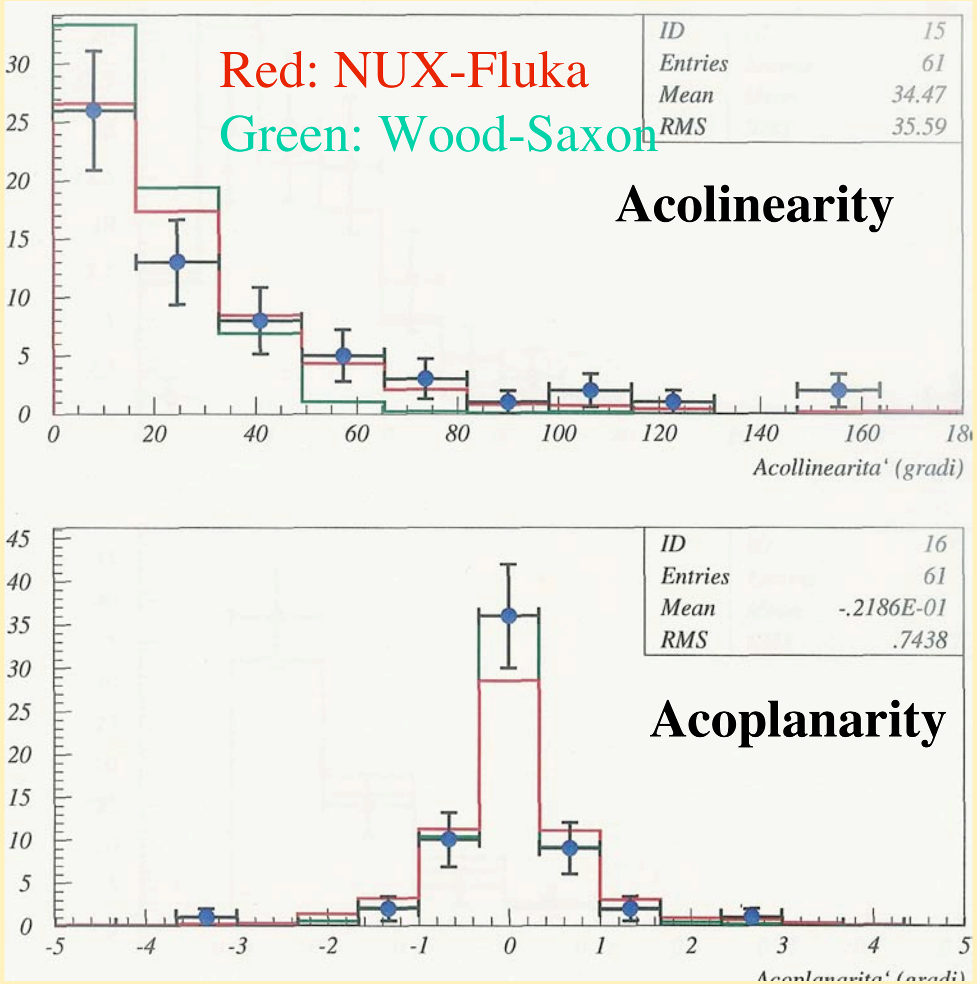
Several months joint-venture ICARUS+INFN Milano+CERN

- 61 golden quasi-elastic selected

B. Boschetti's thesis (Milano, 1998)



$$\nu_\mu + n \rightarrow \mu^- + p$$



- Statistics of ≈2 hours data taking with T2K-LAr!

T2K-LAr detector physics performance studies

- Dedicated simulation tools for T2K-LAr geometry have been developed to assess detector performance
- Results are available on
  - ➥ e/π^0 separation
  - ➥ Hadron identification
  - ➥ Event reconstruction, selection and classification
  - ➥ Stand-alone muon momentum resolution
  - ➥ Neutrino and hadronic system energy resolution
  - ➥ Event kinematics reconstruction
  - ➥ Events in inner target
  - ➥ Nus/antinus statistical separation
- Physics items being studied in details:
  - ➥ Prediction of ν_μ events at SK
  - ➥ Prediction of ν_e events and π^0 background at SK

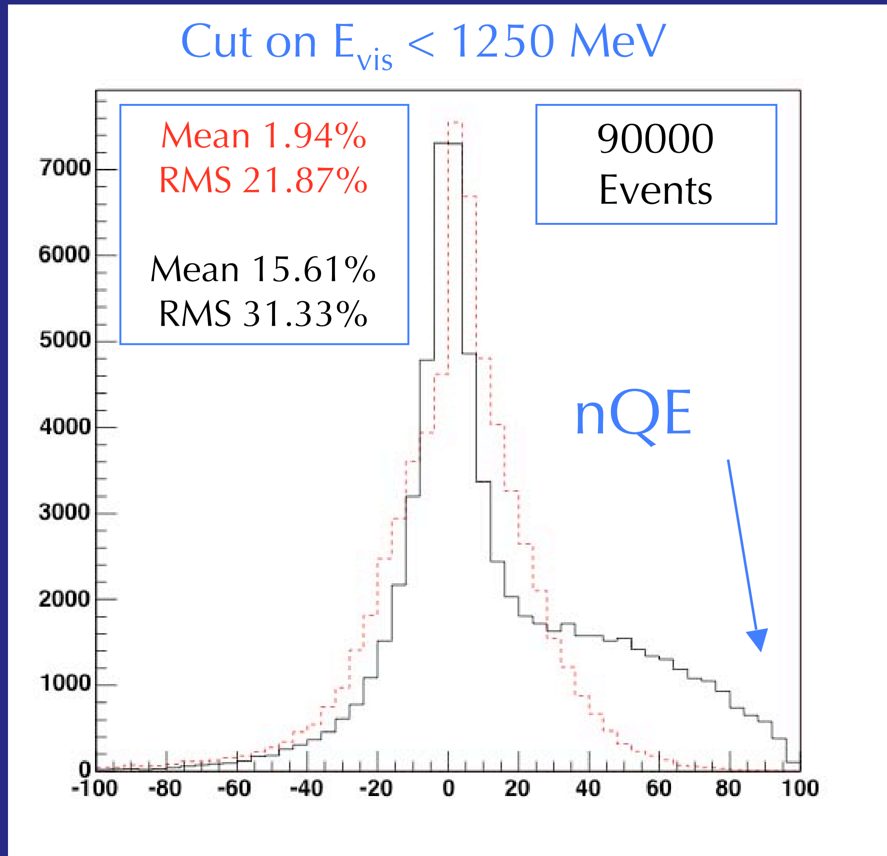
LAr detector performance: neutrino energy reconstruction

——— μ stand alone reconstruction

$$E_\nu^{rec} = \frac{m_N E_\mu - \frac{m_\mu^2}{2}}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

- - - - - - complete reconstruction

$$E_\nu^{rec} = \left|p_\nu^{rec}\right| = \sqrt{\left(\sum p_x\right)^2 + \left(\sum p_y\right)^2 + \left(\sum p_z\right)^2}$$



$(E_\nu^{MC} - E_{vis}) / E_\nu^{MC}$ (%)

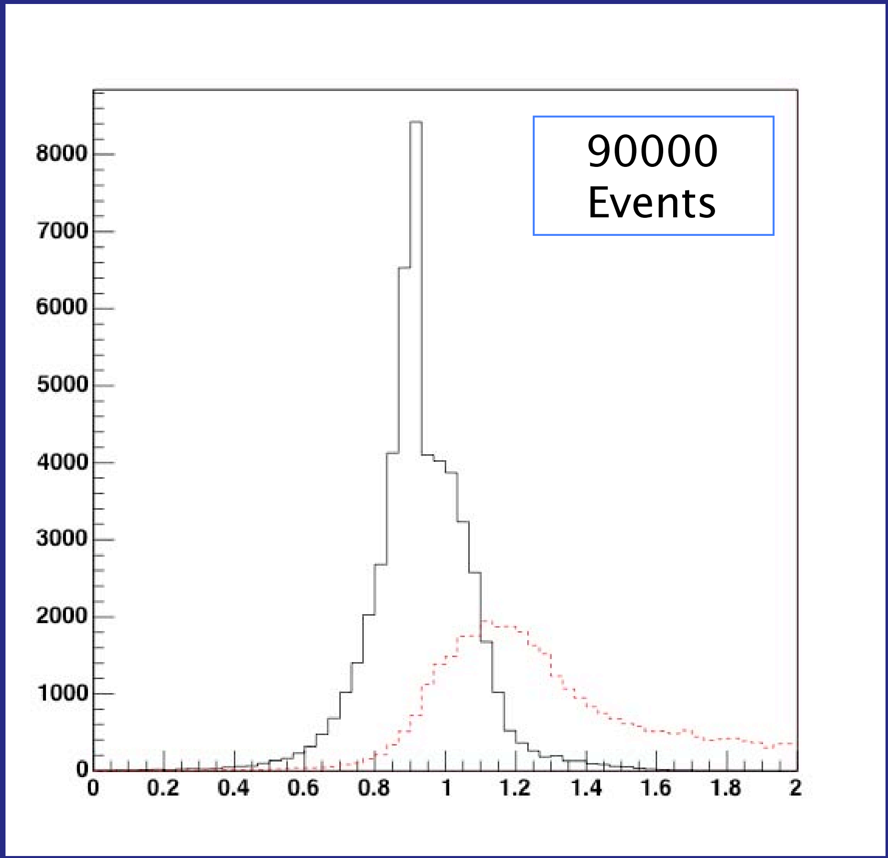
Unbiased visible energy reconstruction

LAr detector performance: QE/nQE measurement

$$Q^2 = 4E_\nu E_\mu \sin^2\theta/2$$

$$W^2 + Q^2 = 2M\nu + M^2$$

$$\nu = E_{had} - M = E_\nu - E_\mu$$



QE interactions (51596 Events)

non-QE interactions (38404 Events)

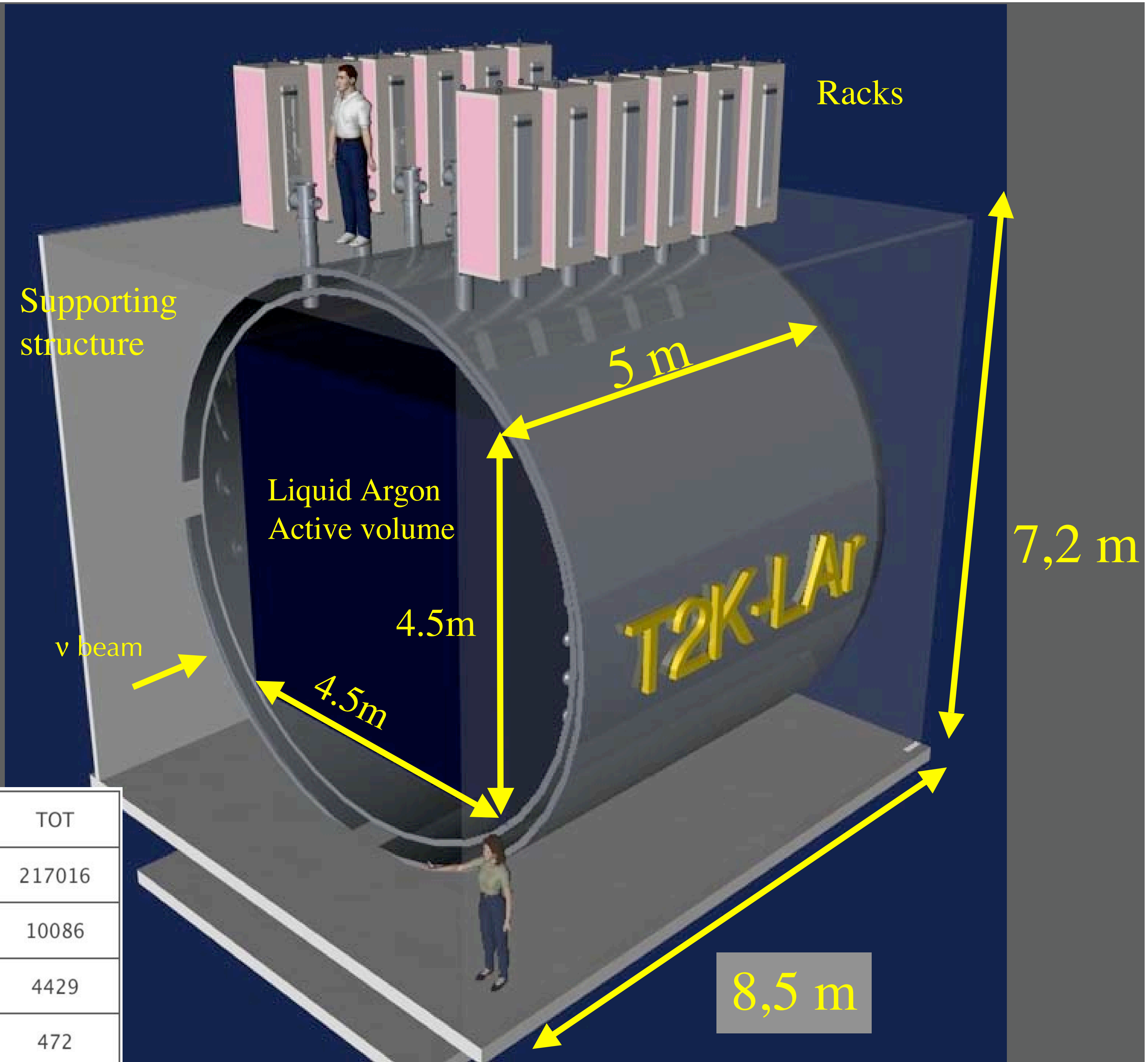
Reconstructed invariant Mass (GeV/c^2)

Physics-driven QE/nQE separation

Design features of T2K-LAr

- The proposed design takes advantage from the experience of ICARUS. However, innovative features and technological advances are included in the detector design. In particular:
  - ➥ Cryostat has a design that follows the codes of conventional cryogenic-fluid pressure storage-vessels (ASME Boiler & Pressure Vessel Code, Sect. VIII (www.asme.org)). Design and construction according to these standards will ensure a reliable and safe cryogenic operation
  - ➥ Cooling is based on heat engine with Ar as medium (avoid LN_2)
  - ➥ Inner detector has an innovative and simple design (to limit complexity & cost)
  - ➥ Immersed Cockroft-Walton to generate uniform drift of 1 kV/cm over 2 m (to exploit very high electric rigidity of LAr)
  - ➥ Inner target allows to measure events on Water / CO_2
  - ➥ New LAr purity monitoring systems
  - ➥ Scintillation light readout based on DUV sensitive PMT
  - ➥ Electronics based on commercial preamps and newly designed digital part (since triggered by beam timing).

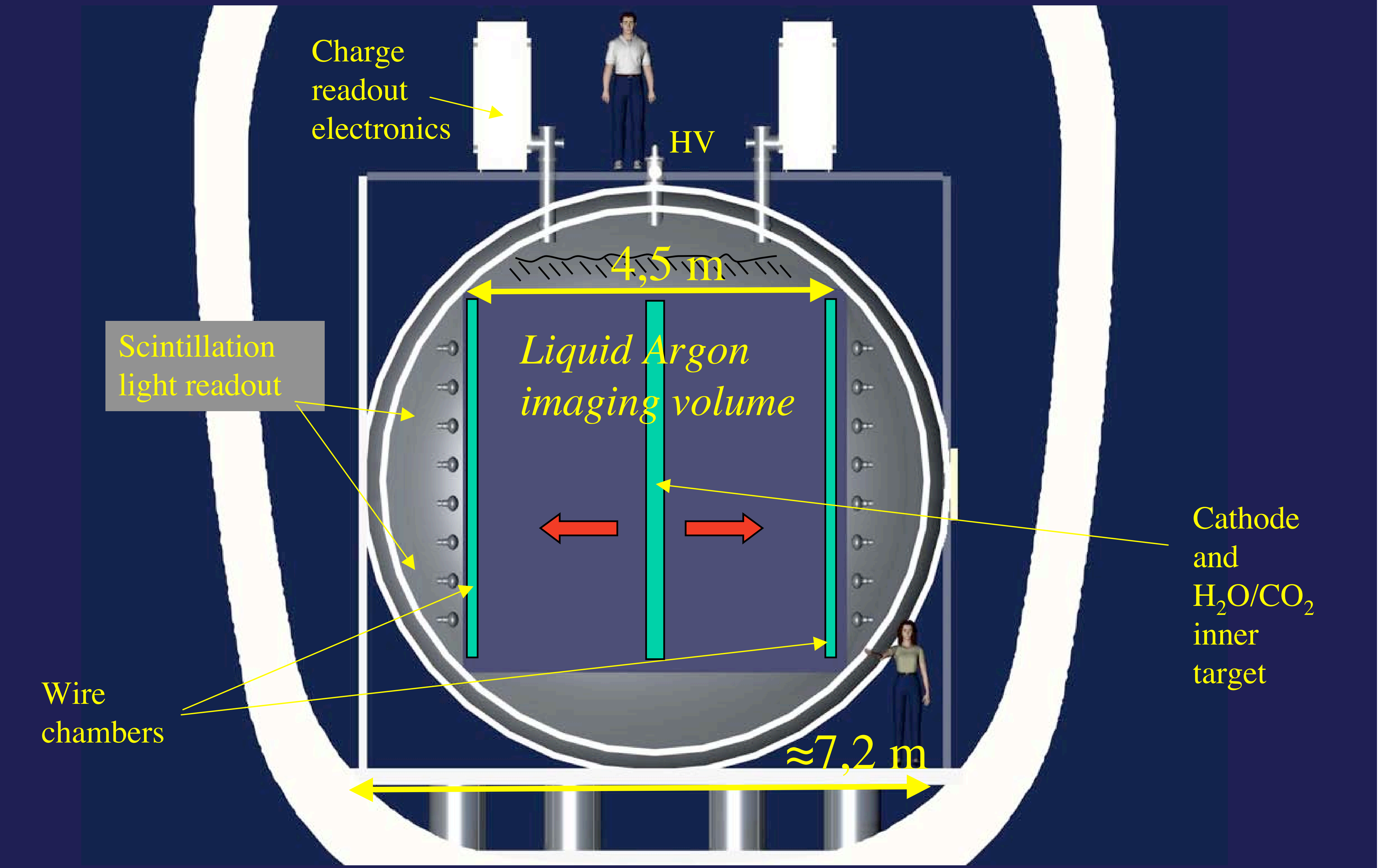
Close view (open endcap)



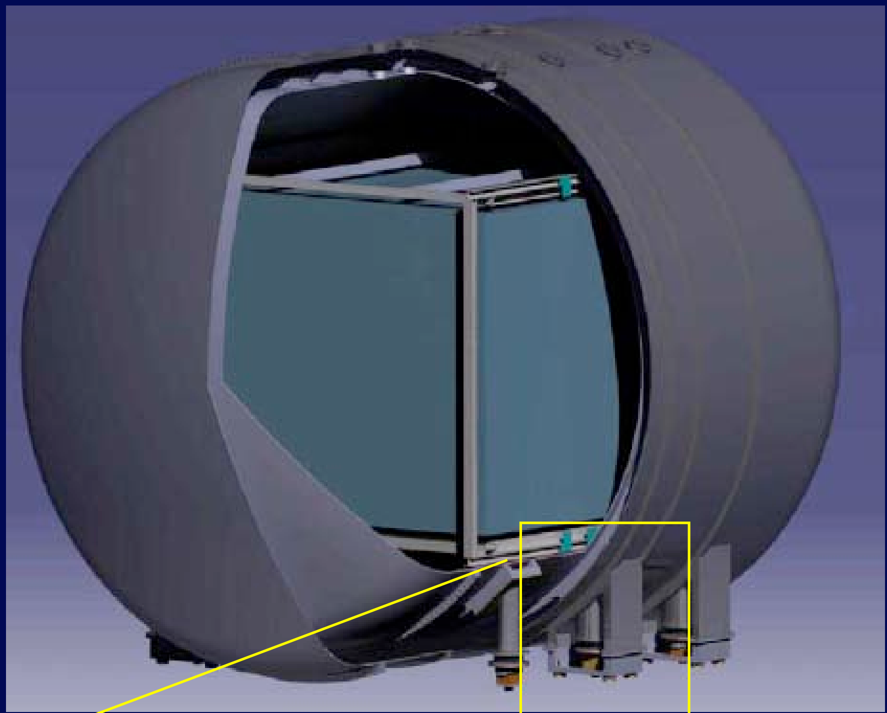
Number of interactions per 10^{21} p.o.t. on a 100 ton detector

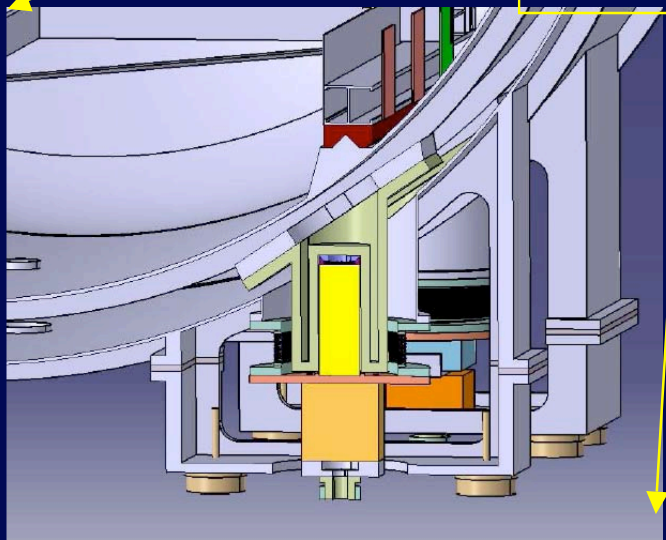
Flavour	CC (QE)	NC	TOT
ν_μ	190763 (121859)	26253	217016
$\bar{\nu}_\mu$	8023 (2764)	2063	10086
ν_e	3704 (1372)	725	4429
$\bar{\nu}_e$	372 (96)	100	472

Front view


Charge
readout
electronics
HV
4,5 m
Liquid Argon
imaging volume
Scintillation
light readout
Cathode
and
H_2O/CO_2
inner
target
Wire
chambers
≈7,2 m

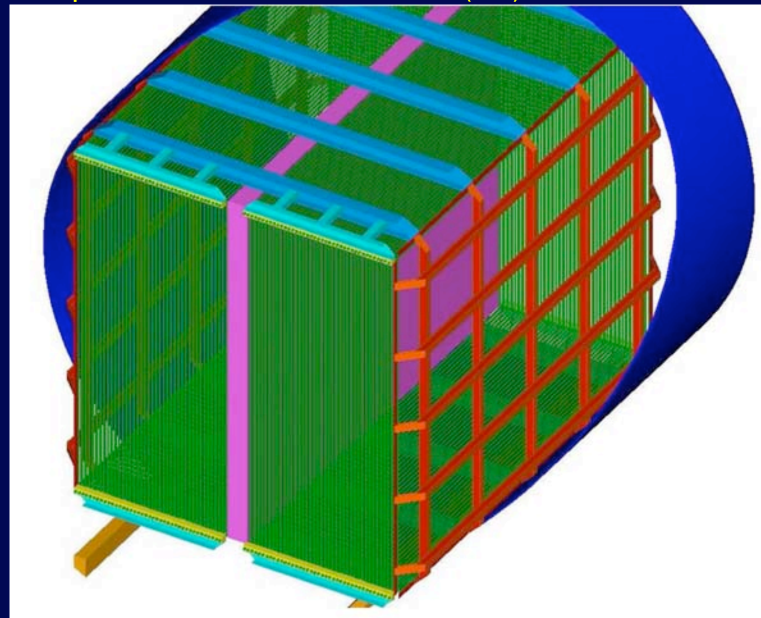
Cryostat design





Inner detector design

4.5 m x 4.5 m x 5 m stainless-steel supporting structure for wire planes, PMTs, auxiliary systems, cathode, inner target.
Two independent readout chambers (LR)

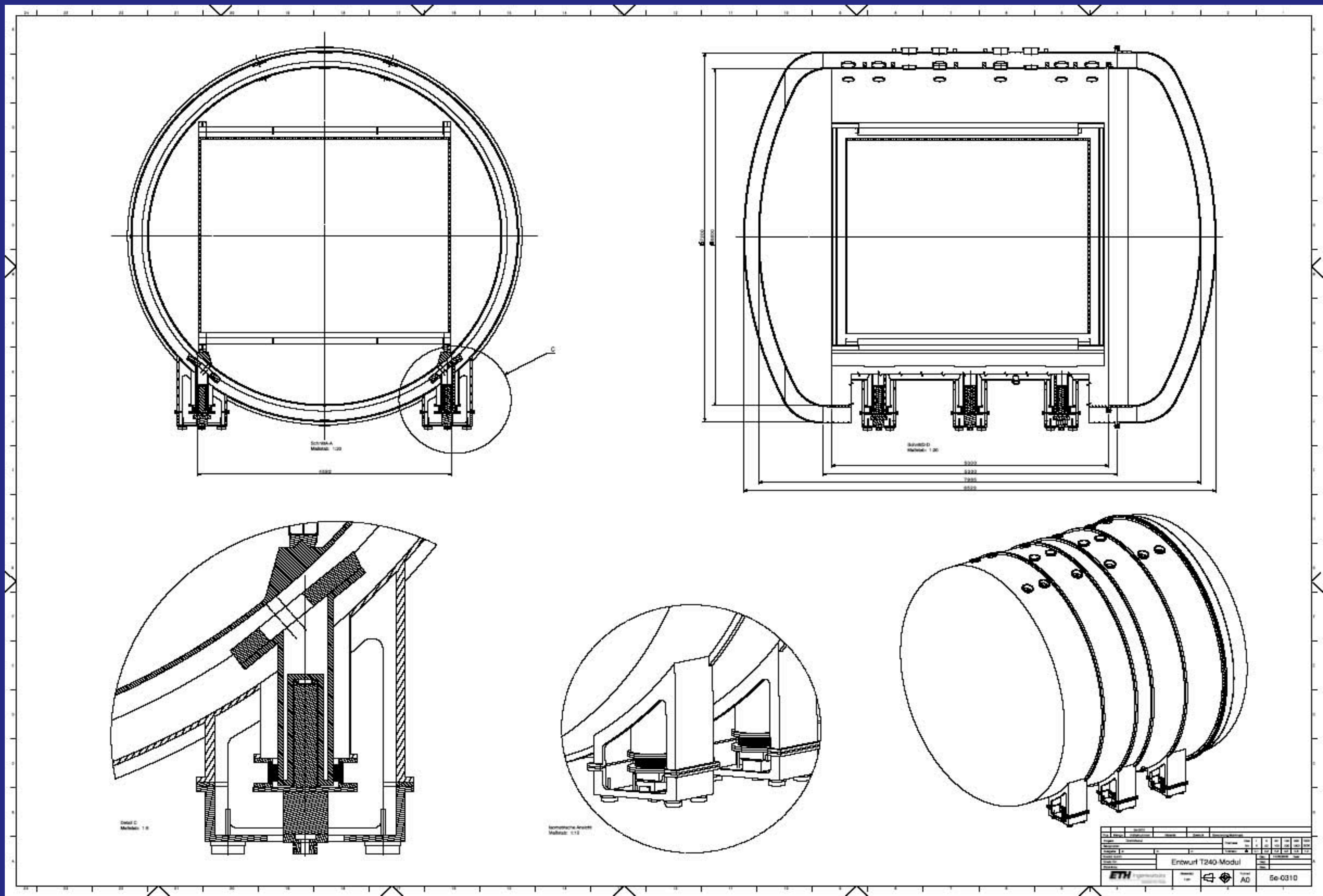


Total LAr mass ≈ 315 tons, total weight ≈ 100 tons, two independent stainless steel vessels, multilayer super-insulation in vacuum.

thermal Insulation	multi-layer super–insulation in vacuum
surface heat input	$1\ W/m^3$
total surface heat input	100 W
(accidental loss of vacuum)	(4 kW)
supporting feet	custom designed
heat input per supporting foot	< 50 W
number of supporting feet	6
total heat input through supporting feet	300 W
signal cables diameter	0.25 mm
length signal cables	0.75 m
number signal cables twisted pairs	10000
total heat input through cables	100 W
total heat input	500 W

Engineering design of cryostat

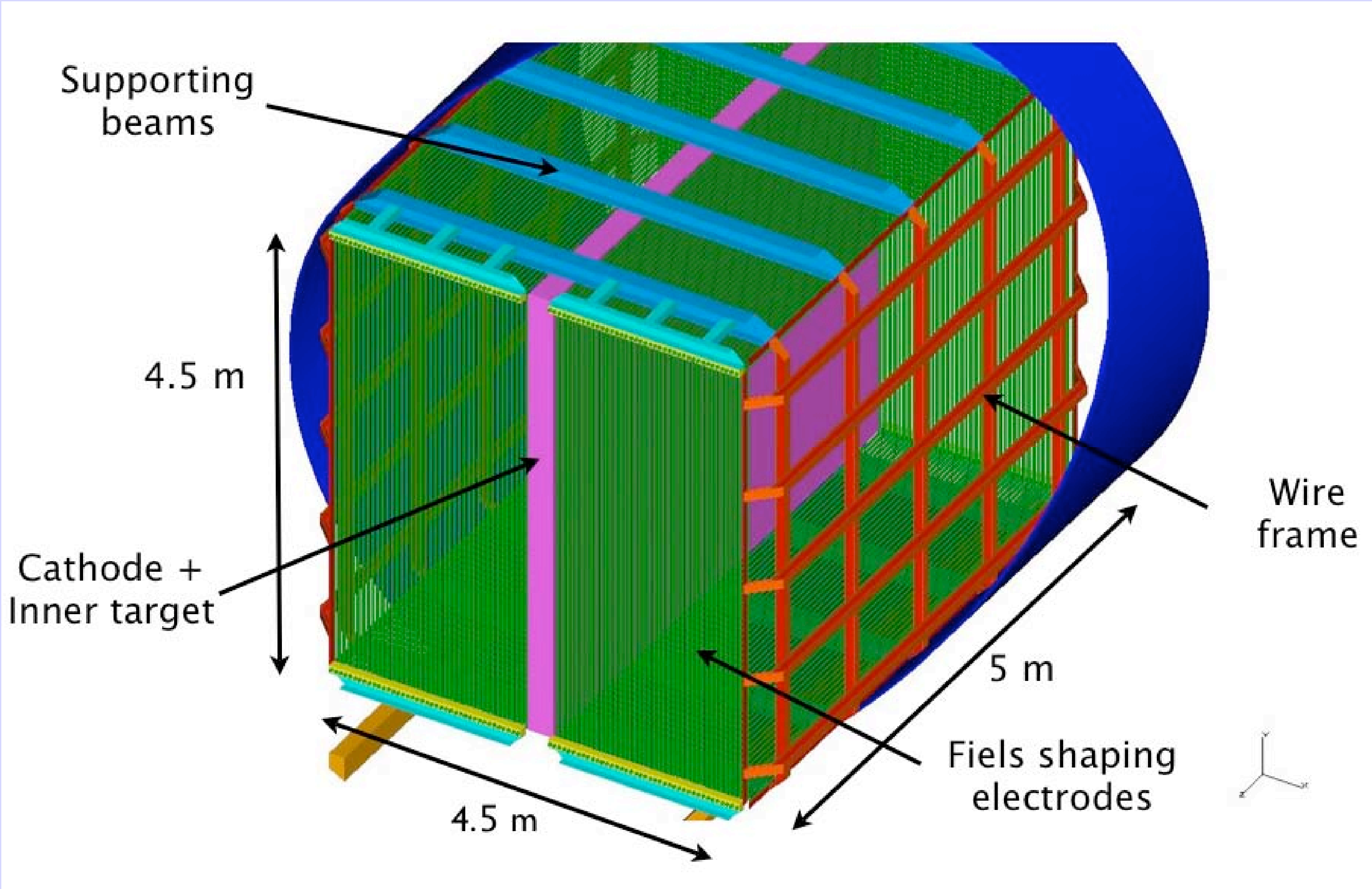
Total LAr mass ≈ 315 tons, total weight ≈ 100 tons, two independent stainless steel vessels, multilayer super-insulation in vacuum.



Inner detector structure

4.5 m x 4.5 m x 5 m stainless-steel supporting structure for wire planes, PMTs, auxiliary systems, cathode, inner target. Two independent readout chambers (LR)

Conceptual design,
stress calculation.

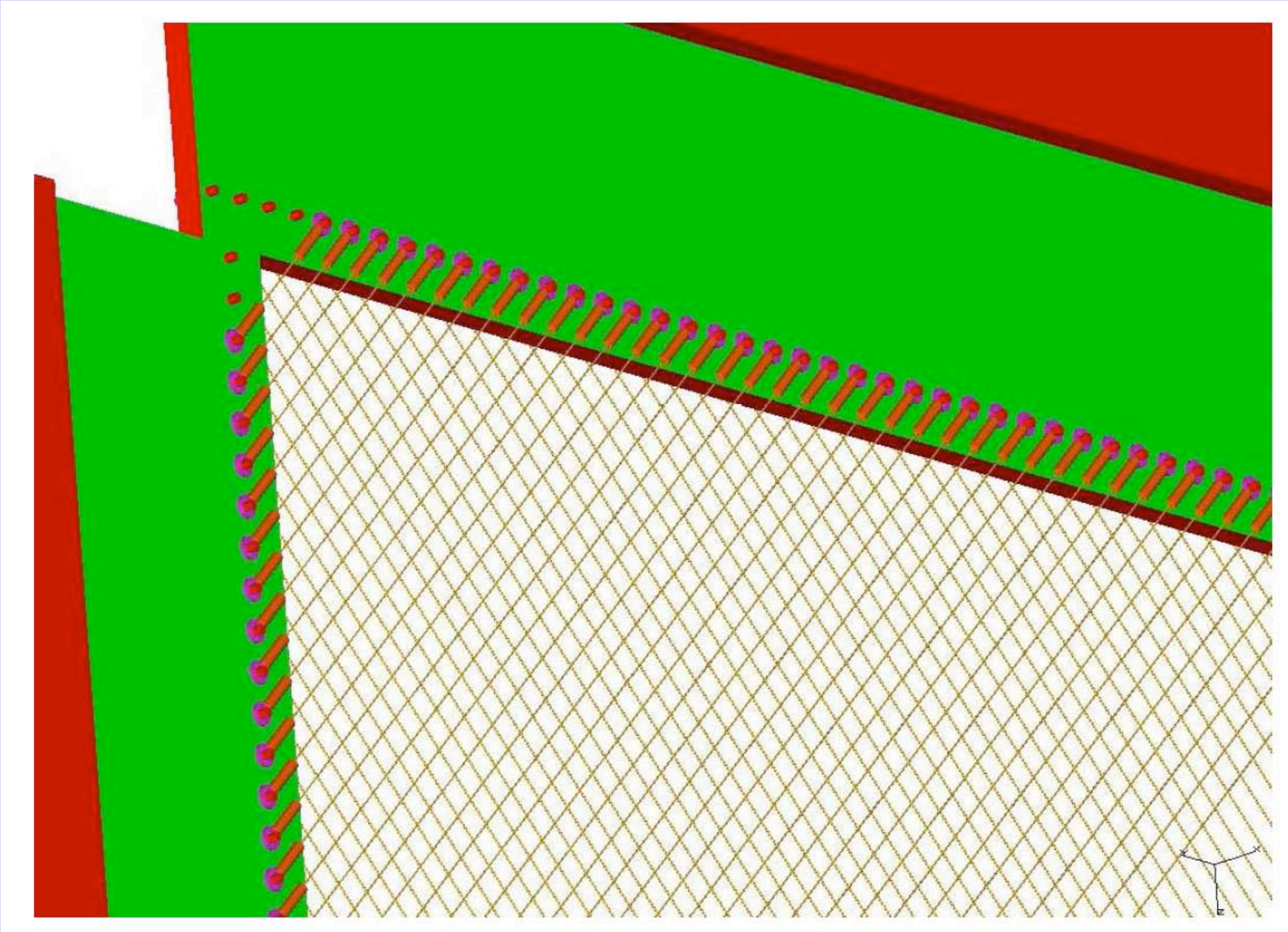


Main parameters of the TPC

number of read-out chambers	2
number of wires planes per chamber	2 (all read-out)
number of optional wires planes per chamber	1 vertical
wires orientation respect to horizontal	$\pm 45^0$
wires orientation respect to horizontal	90^0 (optional)
wires pitch (normal to the wires direction)	3 mm
wires length:	
wires @ $\pm$ 45^0	6.4 m
wires at the borders ($\pm 60^0$)	0 m $\div$ 6.4 m
optional vertical wires (90^0)	4.5 m
wires diameter	150 μm
wires nominal tension	10 N
number of wires / plane:	
wires @ $\pm$ 45^0	118
wires at the borders ($\pm 45^0$)	2120
optional vertical wires (90^0)	1666
number of wires / chamber:	
@ $\pm$ 45^0	236
at the borders ($\pm 45^0$)	4240
optional vertical wires (90^0)	1666
total	4476 (6142)
total number of wires	8952 (12284)
maximum drift length	2.21 m
maximum drift time @1000 V / cm	$\approx$ 1.1 ms
distance between race-tracks axes	40 mm
Imaging volume :	$\approx$ 100 m^3
length	5 m
width	4.5 m
height	4.5 m
total imaging LAr mass	**140 ton**

Details of wire planes

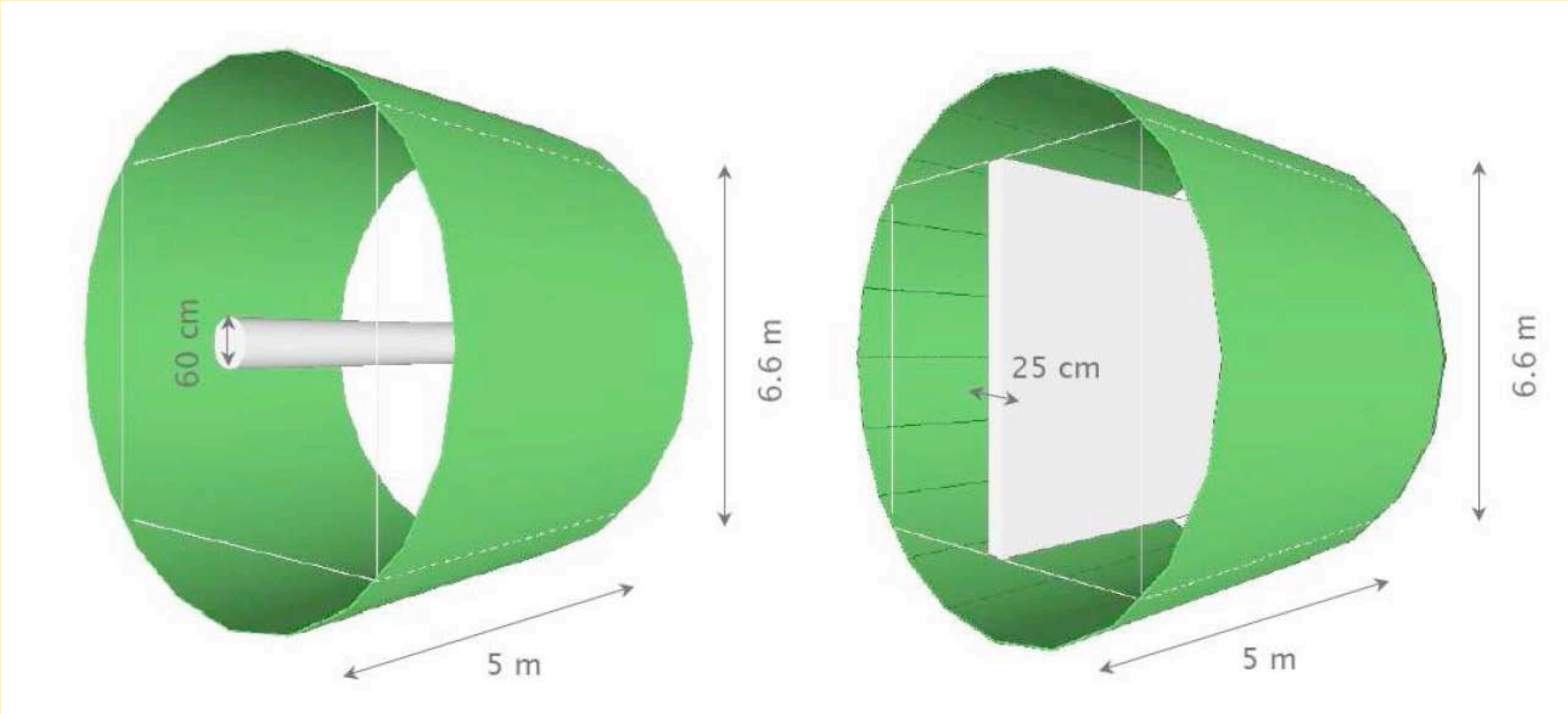
Baseline option: two perpendicular planes per chamber; simple wire sustaining design with wire pre-tensioning anchored by slipknots and pins onto wire frame. Optional third vertical plane under study.



Inner target

- Extrapolation between argon and water targets might still be plagued by uncertainties, which could affect the goal of precision measurements at T2K.
- The "straight-forward" solution is to insert an additional target within the 100 ton LAr detector. This approach (embedded target) is supported by the kinematics of the events (low energy, large angle products, etc.).

geometry	parallel planes	cylinder
length	5 m	5 m
height	4.67 m	-
width	25 cm	-
radius	-	30 cm
outer material	stainless steel 304L	stainless steel 304L
thickness	2 mm	2 mm
inner material	water (Ice)	water (Ice)
inner material density	0.92 g/cm^3	0.92 g/cm^3
mass	5.37 ton	1.30 ton



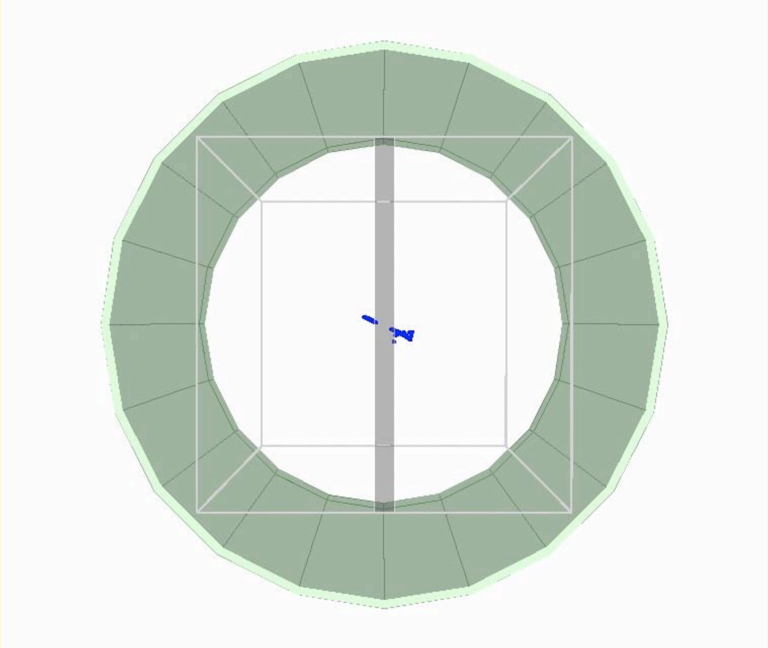
Geometry to be defined following laboratory results and MC simulations

Reconstruction of MC events in inner target

mass width	2.69 ton 12.5 cm	5.37 ton 25 cm	10.74 ton 50 cm
QE protons QE full rec.	50% 36%	30% 22%	19% 14%
QE per 10^{21}pot	**1178**	**1440**	**1832**
nonQE protons nonQE π^+ nonQE π^0 nonQE full rec.	32% 94% 95% 27%	22% 85% 85% 17%	16% 71% 76% 9%
nonQE per 10^{21}pot	**500**	**630**	**670**

QE event in H_2O target:

Recoil proton
p=660 MeV



Light readout system

- Needed for T_0 definition and possibly independent trigger
- Two possible options
  - ➥ (A) 8” PMT with WLS coating
  - ➥ (B) 2” PMTs with MgF_2 window glass for DUV sensitivity
  - ➥ Immersed in LAr
- Number of PMTs : 60÷150
- HV distribution designed (minimize #feed-through, power dissipation, …)

High voltage system

- Cathode @ 200 kV + field shaping electrodes designed
- Uniform drift field ≈ 1 kV/cm
- Immersed Cockroft-Walton HV generator (no HV feed-throughs)
- Mechanical tolerance studied
- Field mill for field measurement

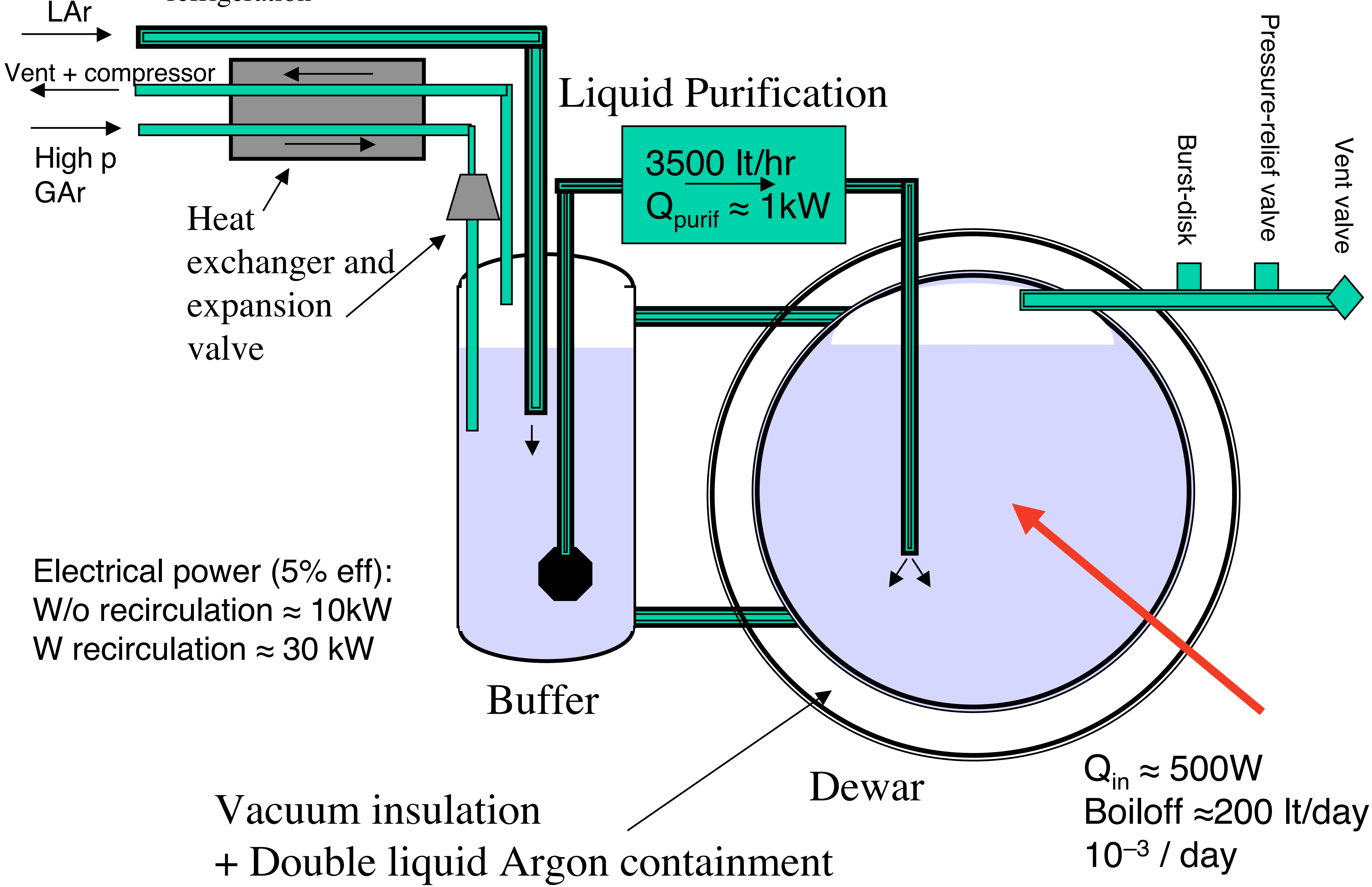
Readout electronics

- Commercially available front-end analog board (CAEN, 32 channels)
- Custom-made digital boards to interface to PCs
- ≈10’000 channels in total

LAr purity monitors and slow control

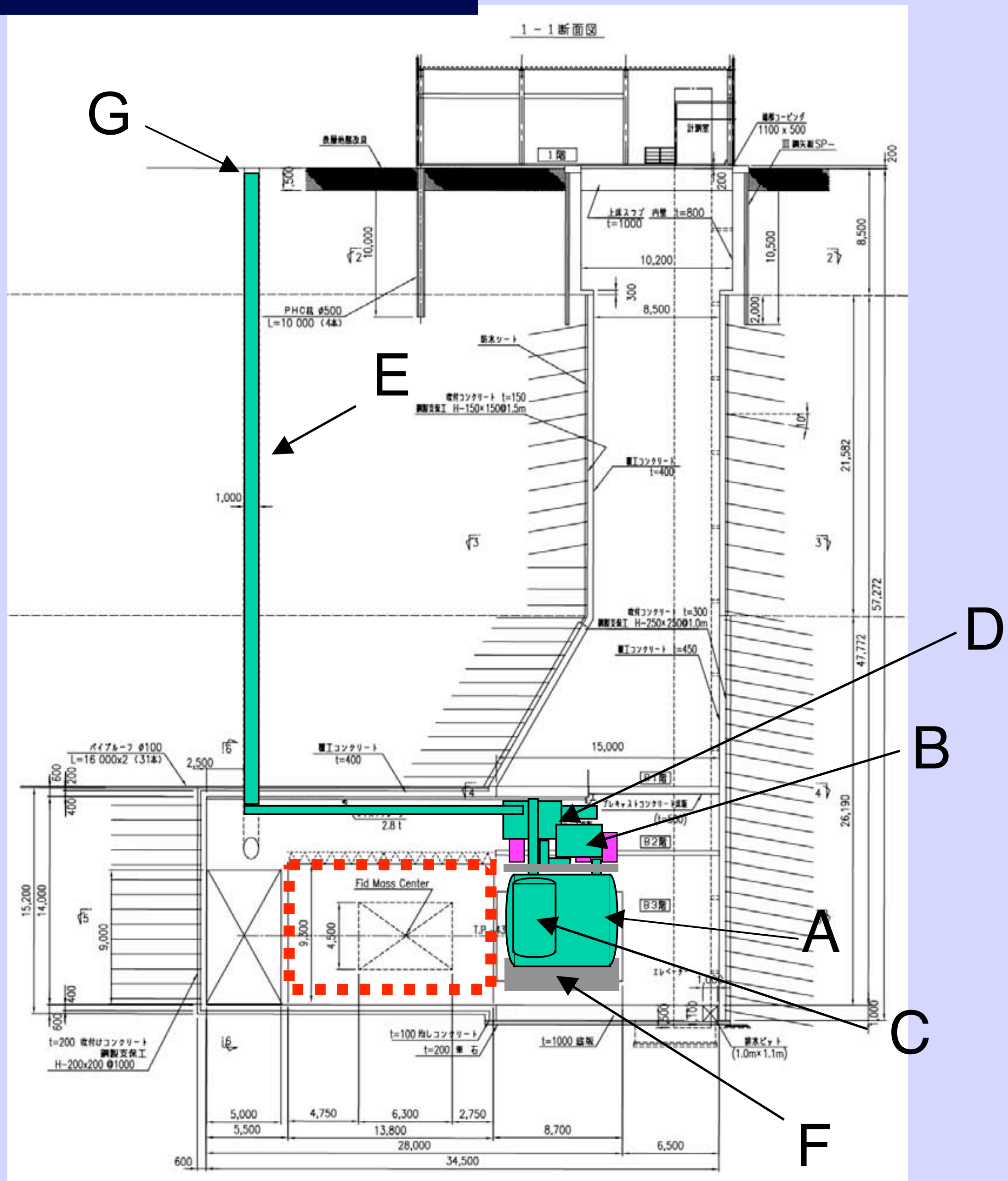
- Improved designs of previously custom-built devices. Study of UV laser calibration

Liquid Argon process

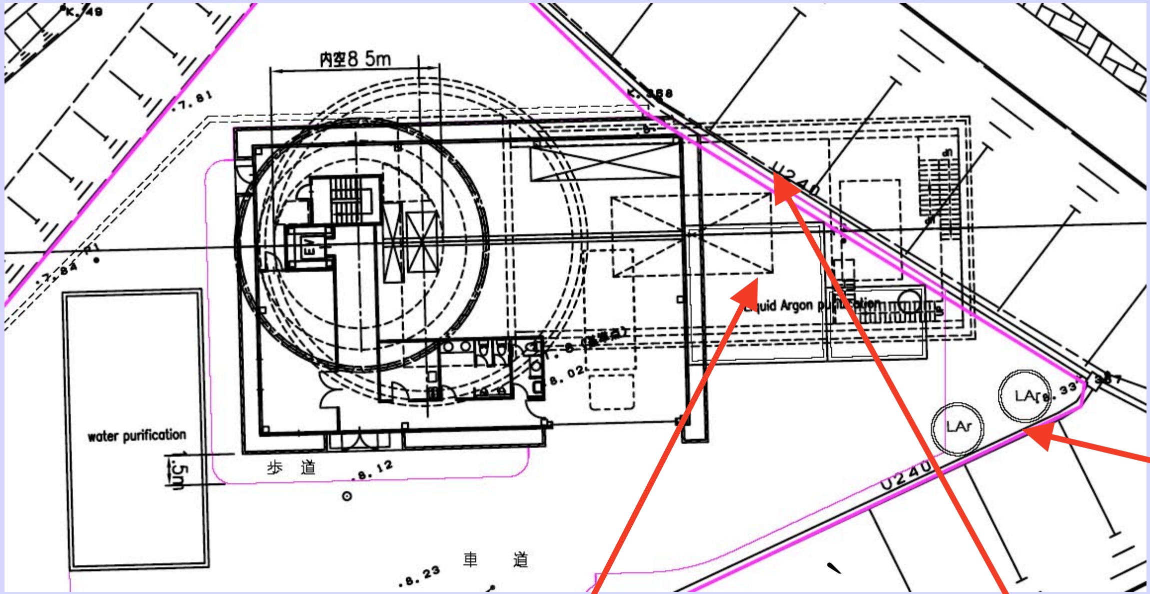


Underground cryogenic infrastructure

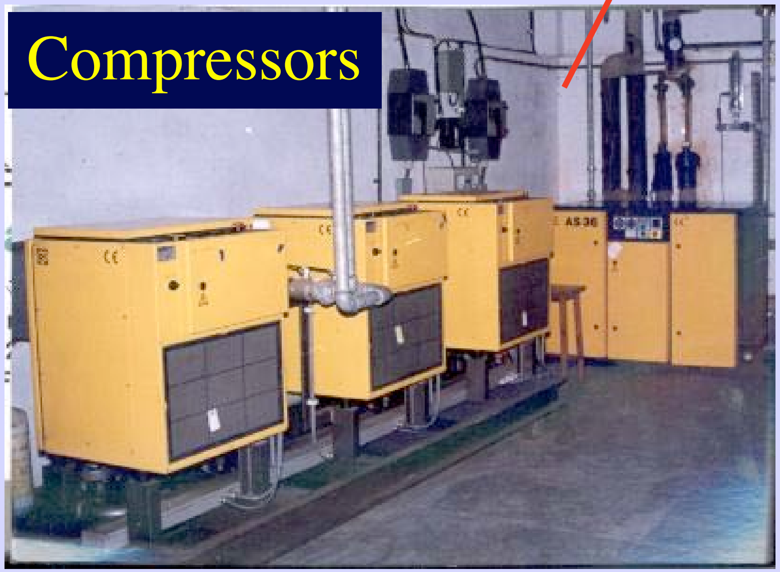
A: Detector dewar
B: LAr Purification
C: Buffer
D: Heat exchanger and expansion valve
E: Argon pipes
F: Shock absorbers
G: Dedicated shaft (ventilation+piping)



Surface infrastructure



A preliminary layout of the needed surface equipment has been outlined



Compressors

Vaporizers

LAr storage

Summary: what the liquid Argon TPC adds to T2K 2km

- Particles with very low momentum, well below Cerenkov threshold, are visible, especially protons
- Independent measurement of off-axis flux and non-QE/QE event ratio
- Exclusive measurement of NC and intrinsic electron neutrino background. Excellent PID allows these to be separately measured
- Study the same class of events in LAr and WC to better understand the systematics of the WC reconstruction and SK extrapolation
- High statistics neutrino interaction studies with bubble chamber accuracy

Preliminary cost estimates

Cost Estimate for 2KM with Breakdown by Region/Country

in units of $M	Total	U.S.	Japan	Europe	Other
Water Cherenkov	8.3	4.2	4.2	0	0
Muon Range Detector	3.8	0	0	0	3.8
Liquid Argon	12.6	1.9	0	10.7	0
Civil Construction	11.9	6.0	6.0	0	0
Total	36.6	12.0	10.1	10.7	3.8

Notes: proposed breakdown: 15%-85% for LAr, 50%-50% for WC+civil construction
treat MRD as contingency cost to Japan; seek contribution from new group(s)
estimated operating costs $385,000/yr, propose to be born equally U.S./Japan/Europe

Submitted to DOE/NSF NUSAG committee in May 2005

Outlook

- The approved T2K experiment in Japan will provide the ideal conditions for long-baseline neutrino physics beyond the current round of experiments (K2K, MINOS, CNGS) and long-term future neutrino facilities will benefit from its results (branch-point?).
- The 2km position is unique and will allow to fruitfully exploit the high statistical accuracy by providing means to reach small systematic errors. It adds clearly identifiable value to the T2K experiment.
- The 2km group is a strong international effort. The WC technology is well understood and economical. The liquid Argon TPC is a novel technology, developed during many R&D by the ICARUS Collaboration, with large potentials for future facilities.

The 2km facility is the most straight-forward and cost-effective method to reach the best possible sensitivity in θ_{13} , Δm^2 and θ_{23} by characterizing the beam with the same flux and target as SuperK.